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(54) **ELECTRONIC DEVICE INCLUDING TRENCHES AND DISCONTINUOUS STORAGE ELEMENTS**

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(51) **Int. Cl.**
H01L 29/76 (2006.01)
(52) **U.S. Cl.** .. 257/314; 257/316; 257/331; 257/E29.264
(58) **Field of Classification Search** 257/314-326, 257/330-332, 366, E29.3, E29.262, E29.264
See application file for complete search history.

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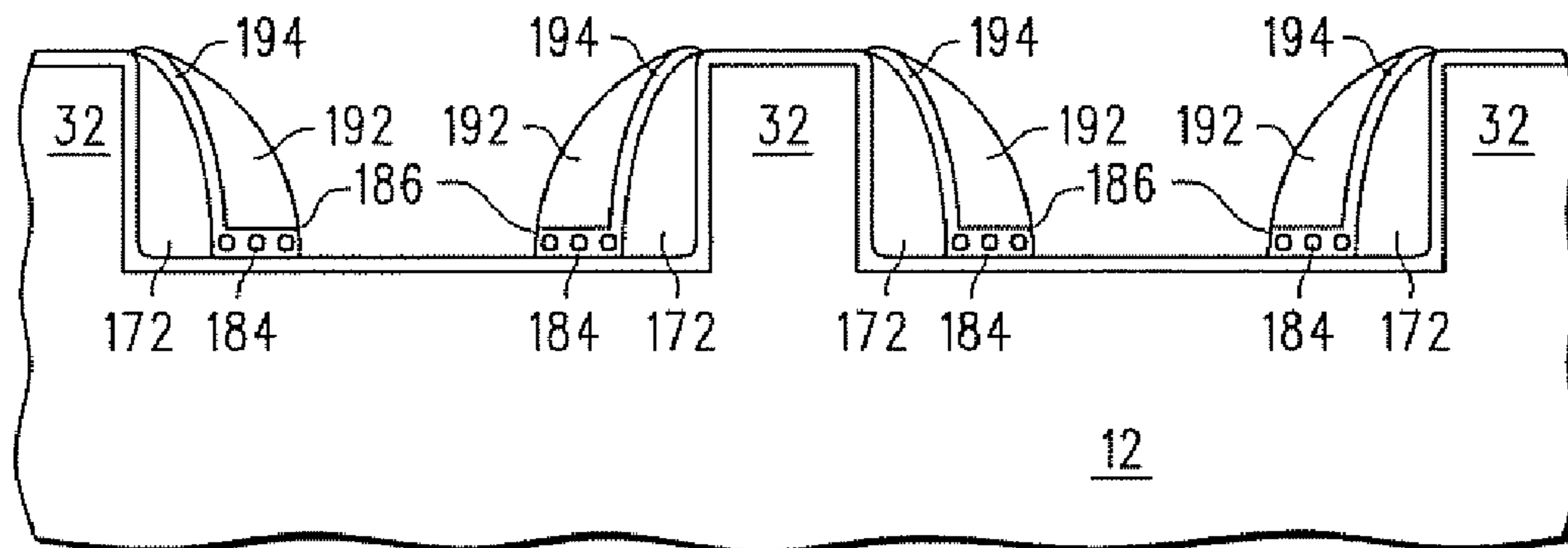
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(57) **ABSTRACT**

An electronic device can include a substrate including a first trench having a first bottom and a first wall. The electrode device can also include a first gate electrode within the first trench and adjacent to the first wall and overlying the first bottom of the first trench, and a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the first bottom of the first trench. The electronic device can further include discontinuous storage elements including a first set of discontinuous storage elements, wherein the first set of the discontinuous storage elements lies between (i) the first gate electrode or the second gate electrode and (ii) the first bottom of the first trench. Processes of forming and using the electronic device are also described.

17 Claims, 13 Drawing Sheets



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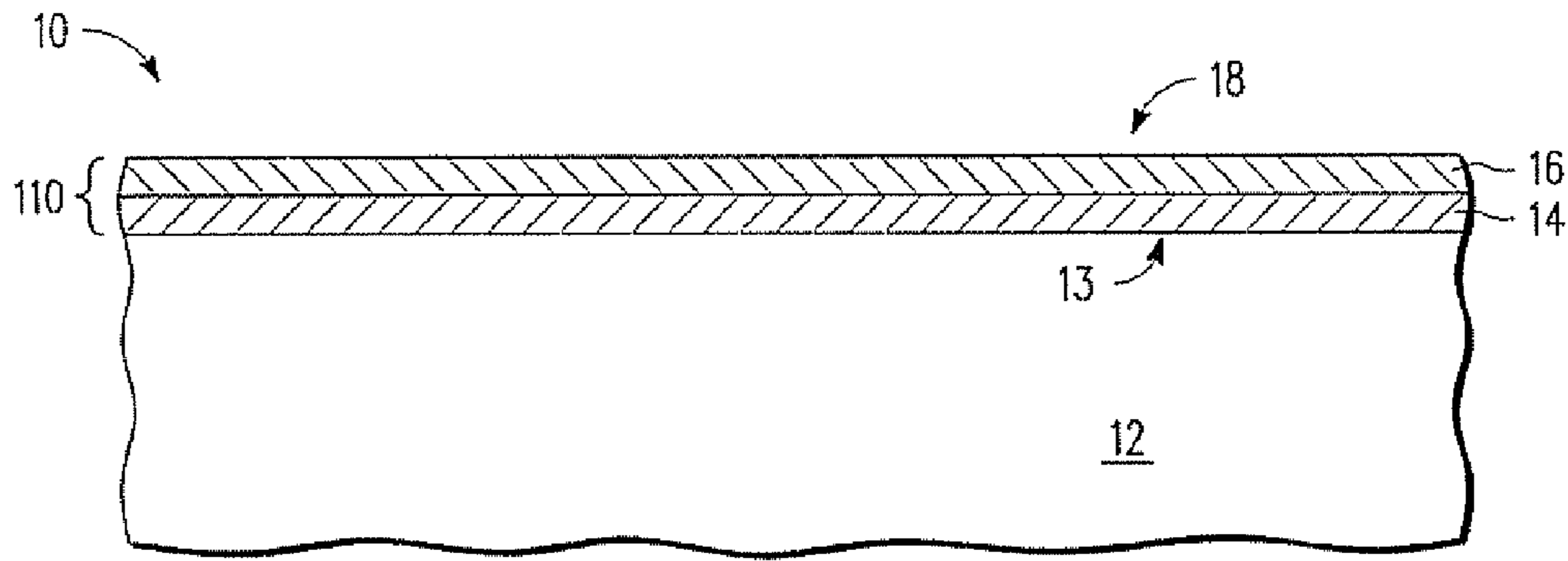


FIG. 1

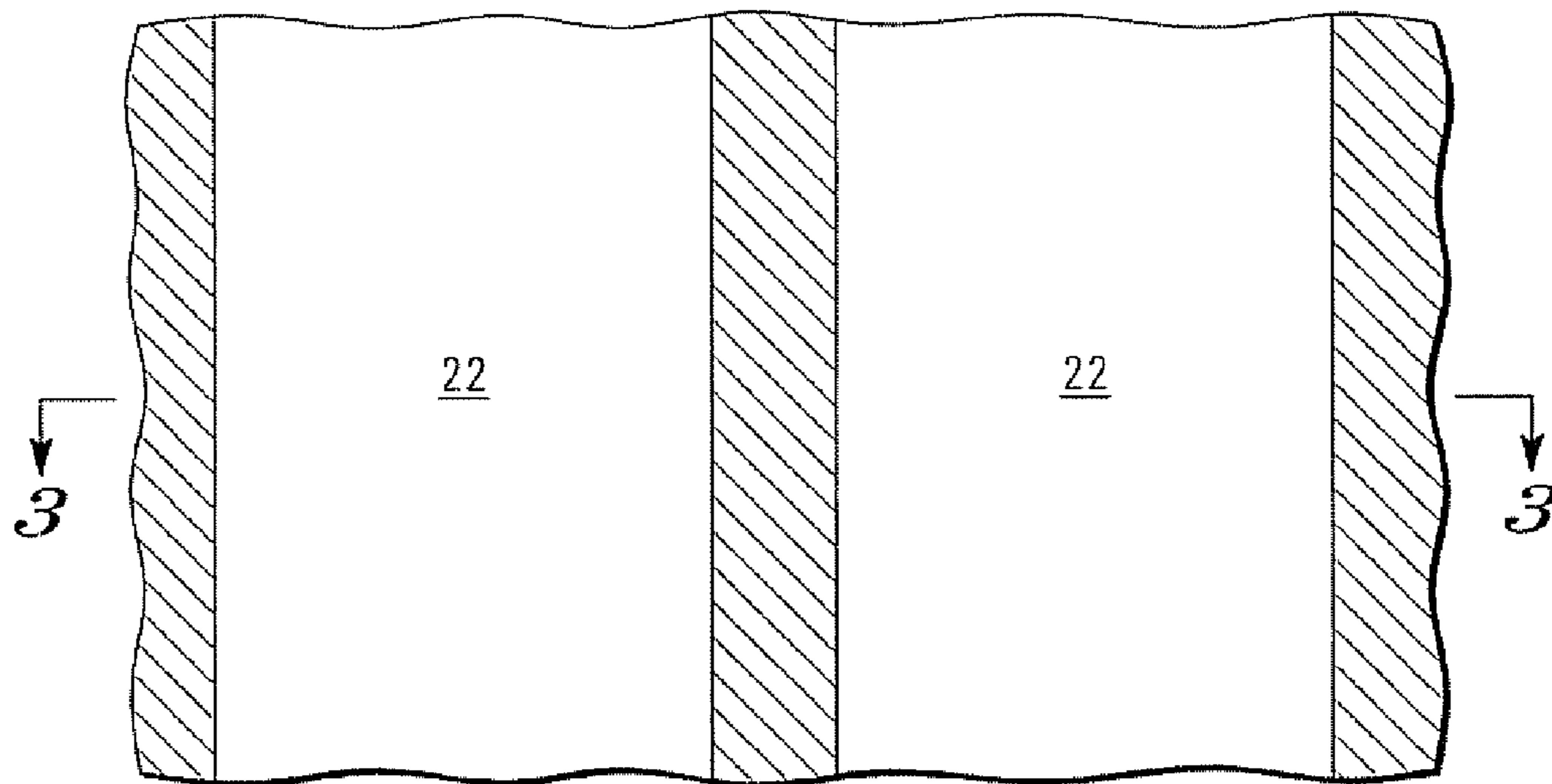


FIG. 2

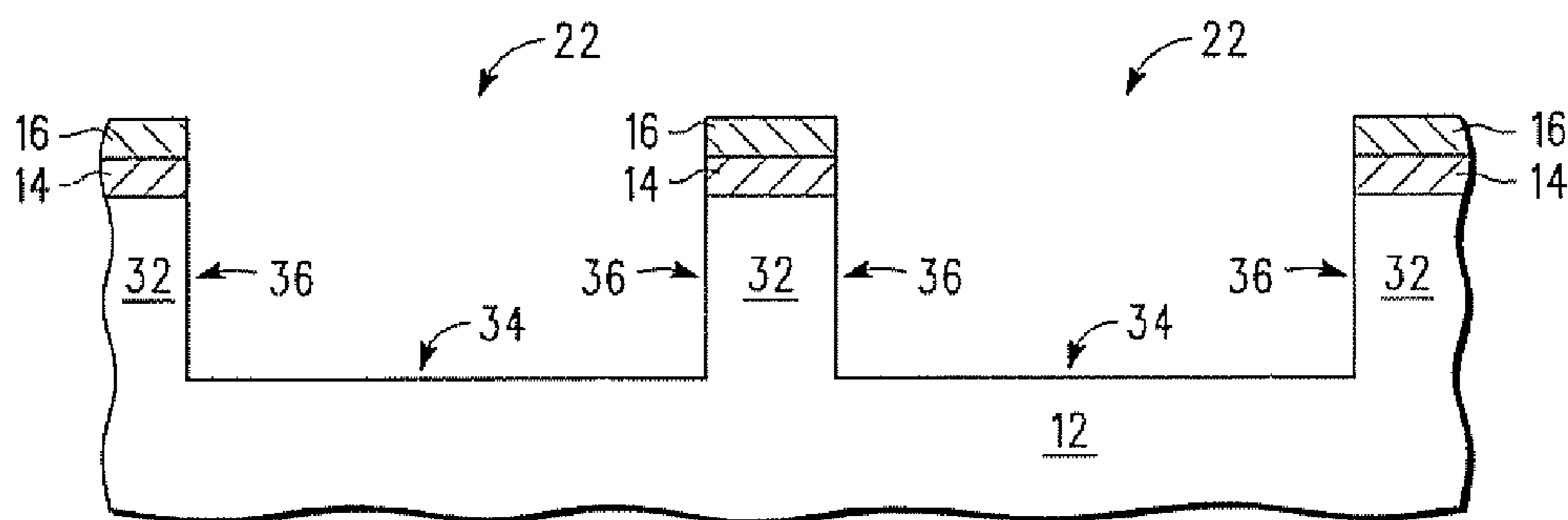


FIG. 3

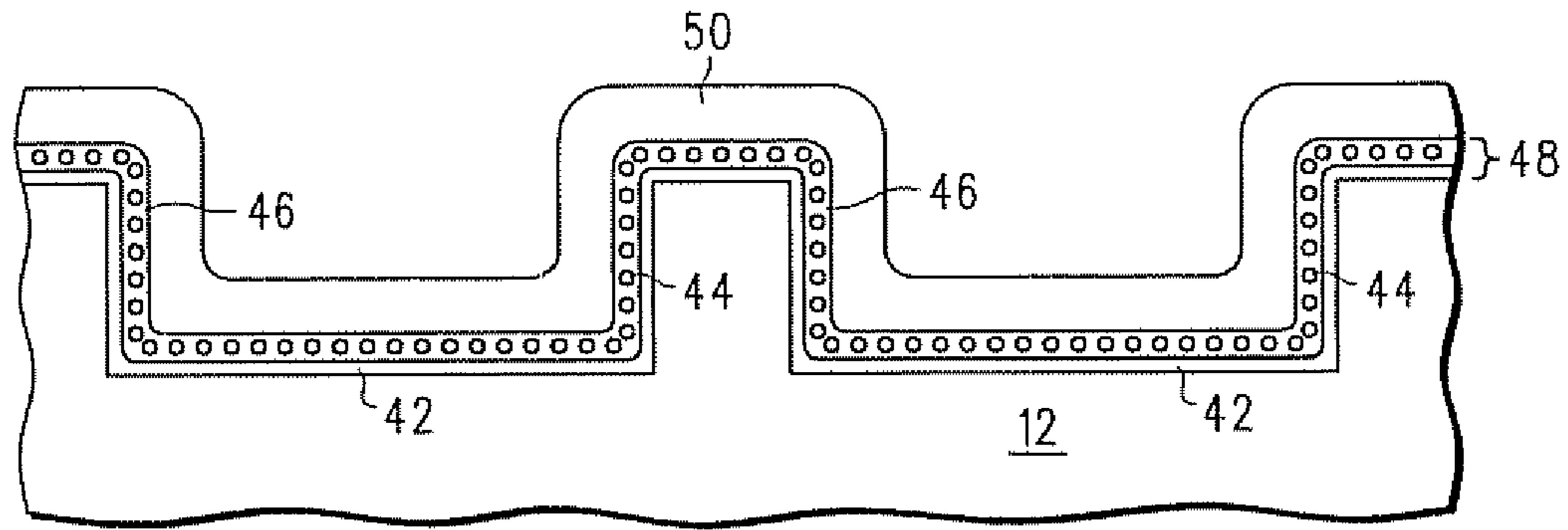


FIG. 4

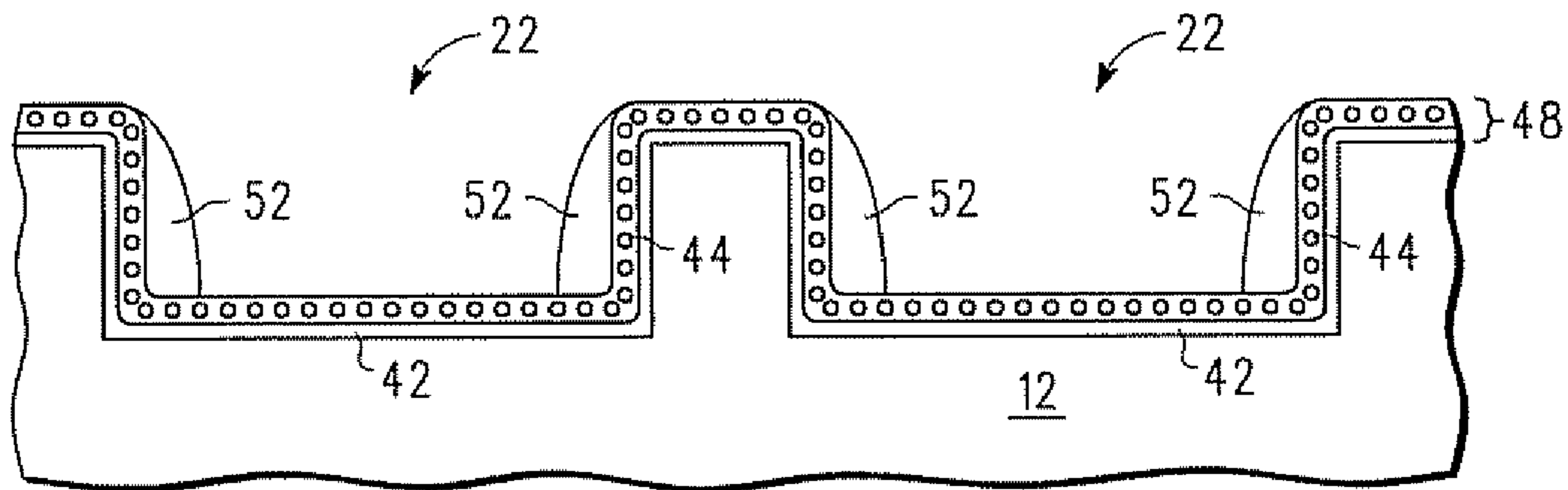


FIG. 5

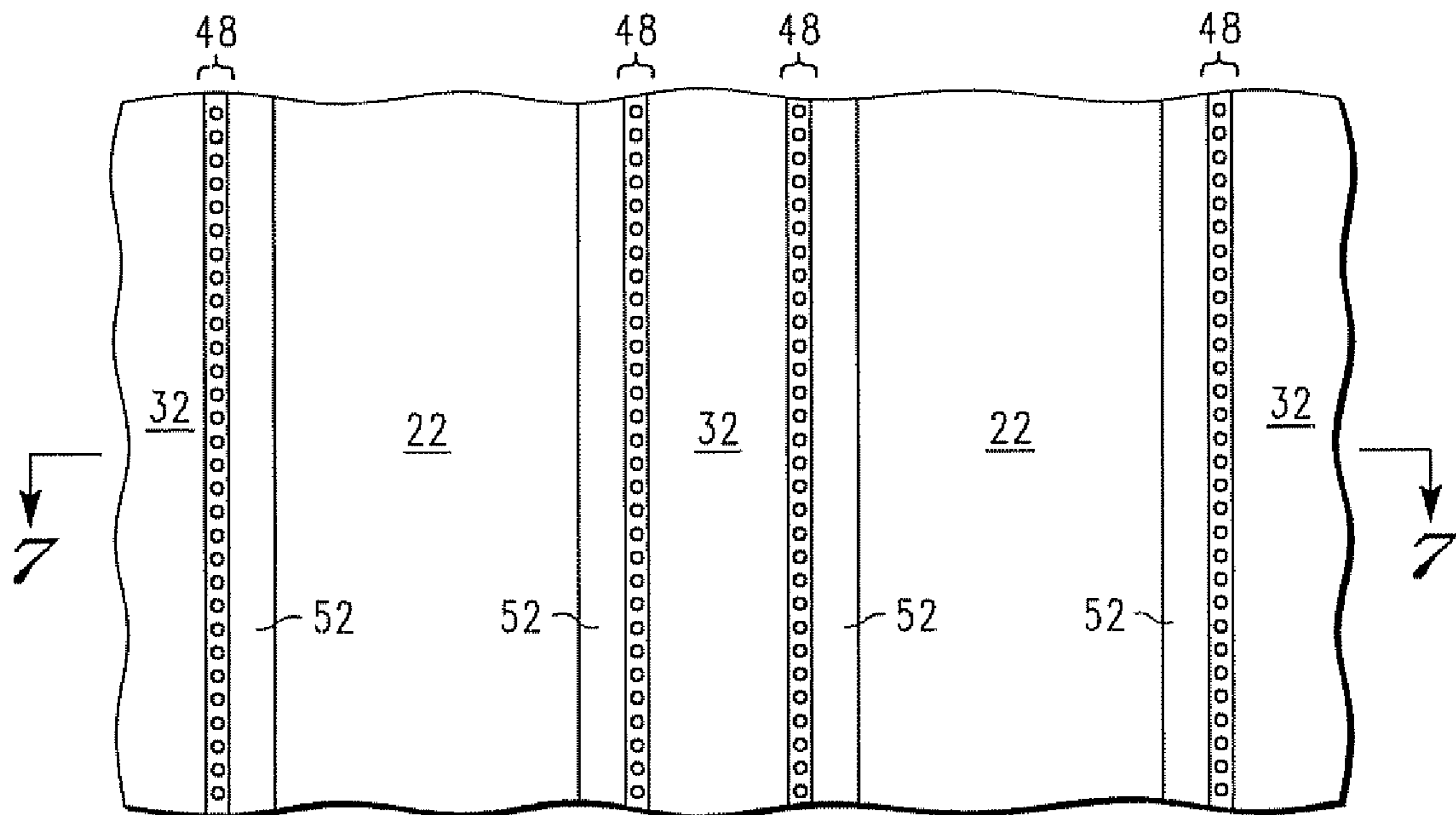


FIG. 6

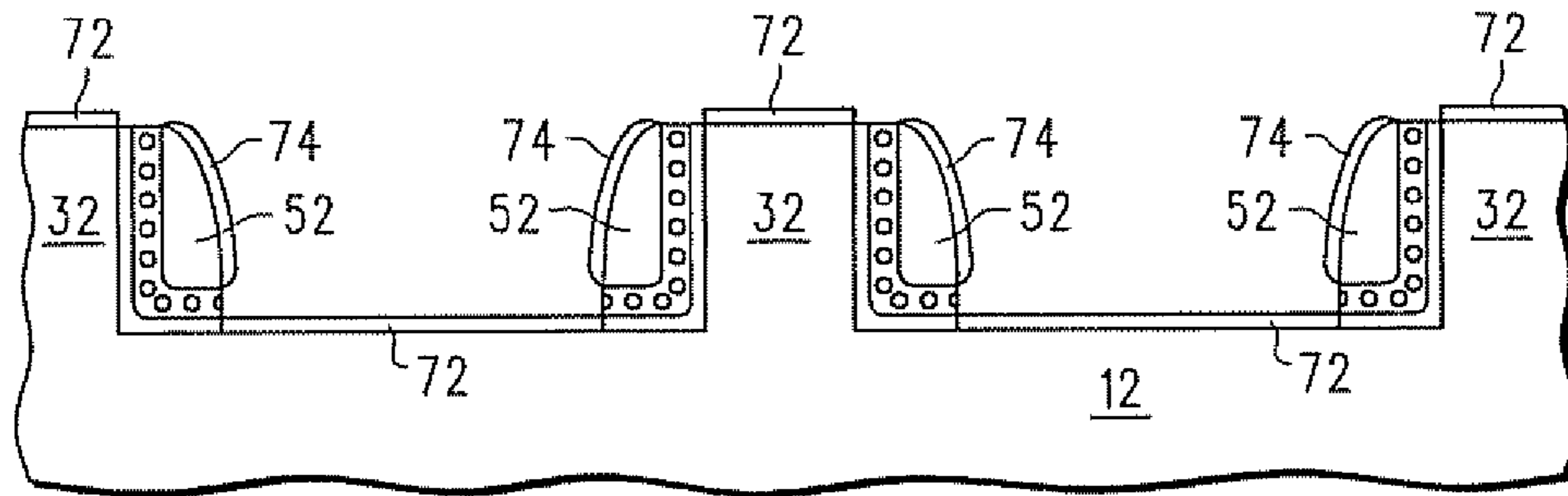


FIG. 7

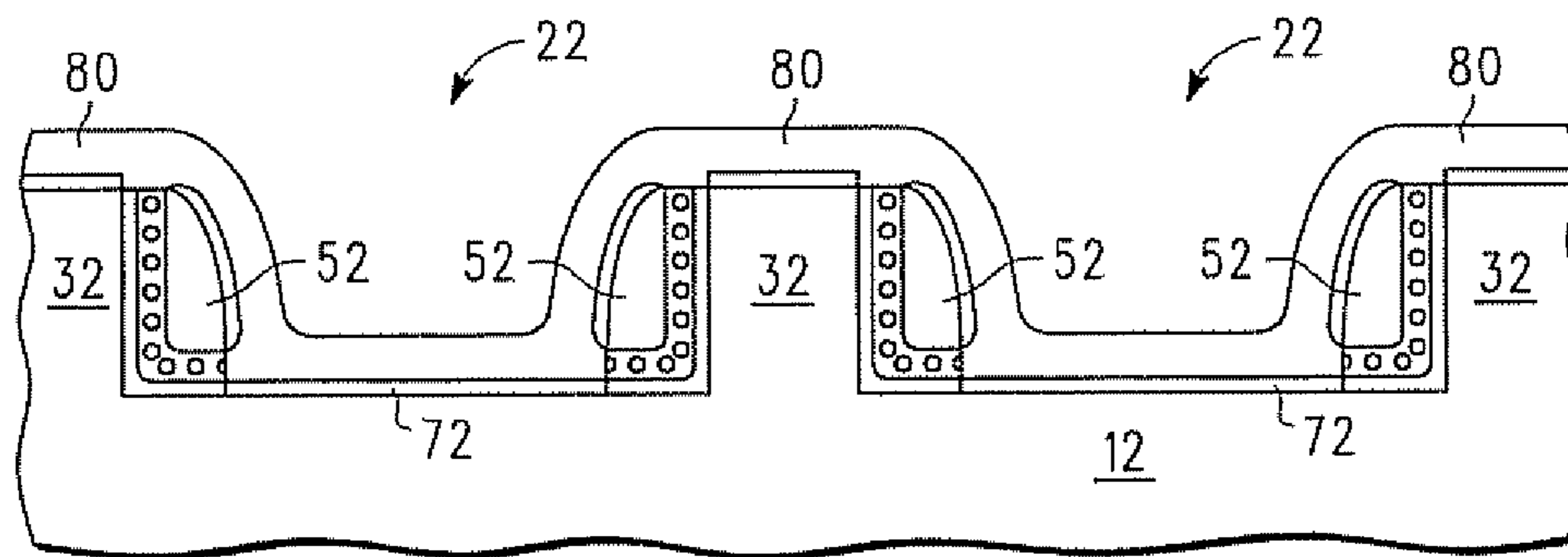


FIG. 8

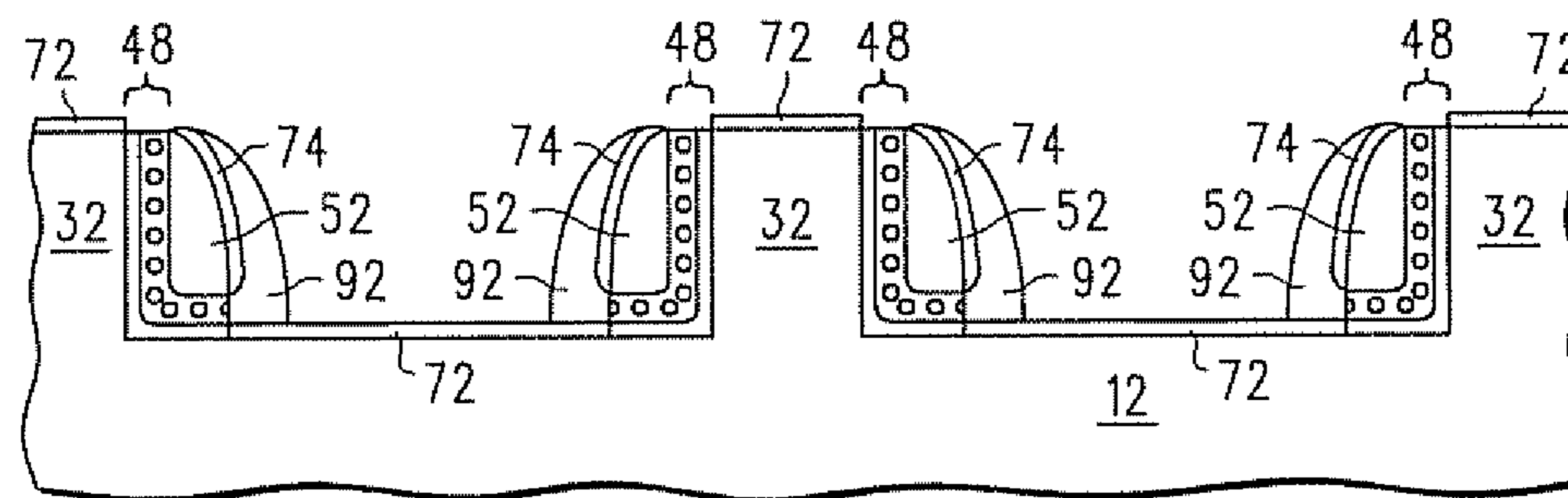


FIG. 9

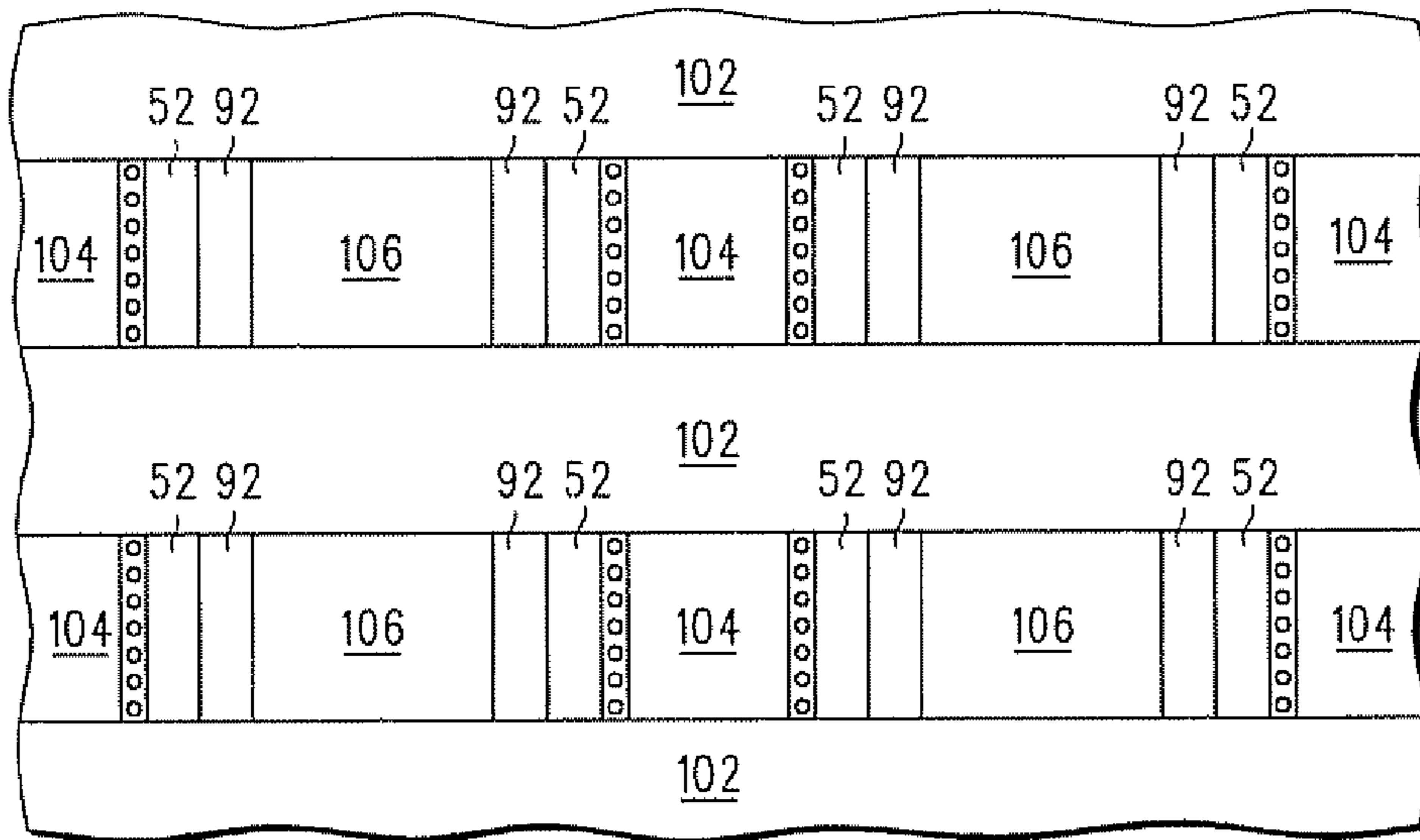


FIG. 10

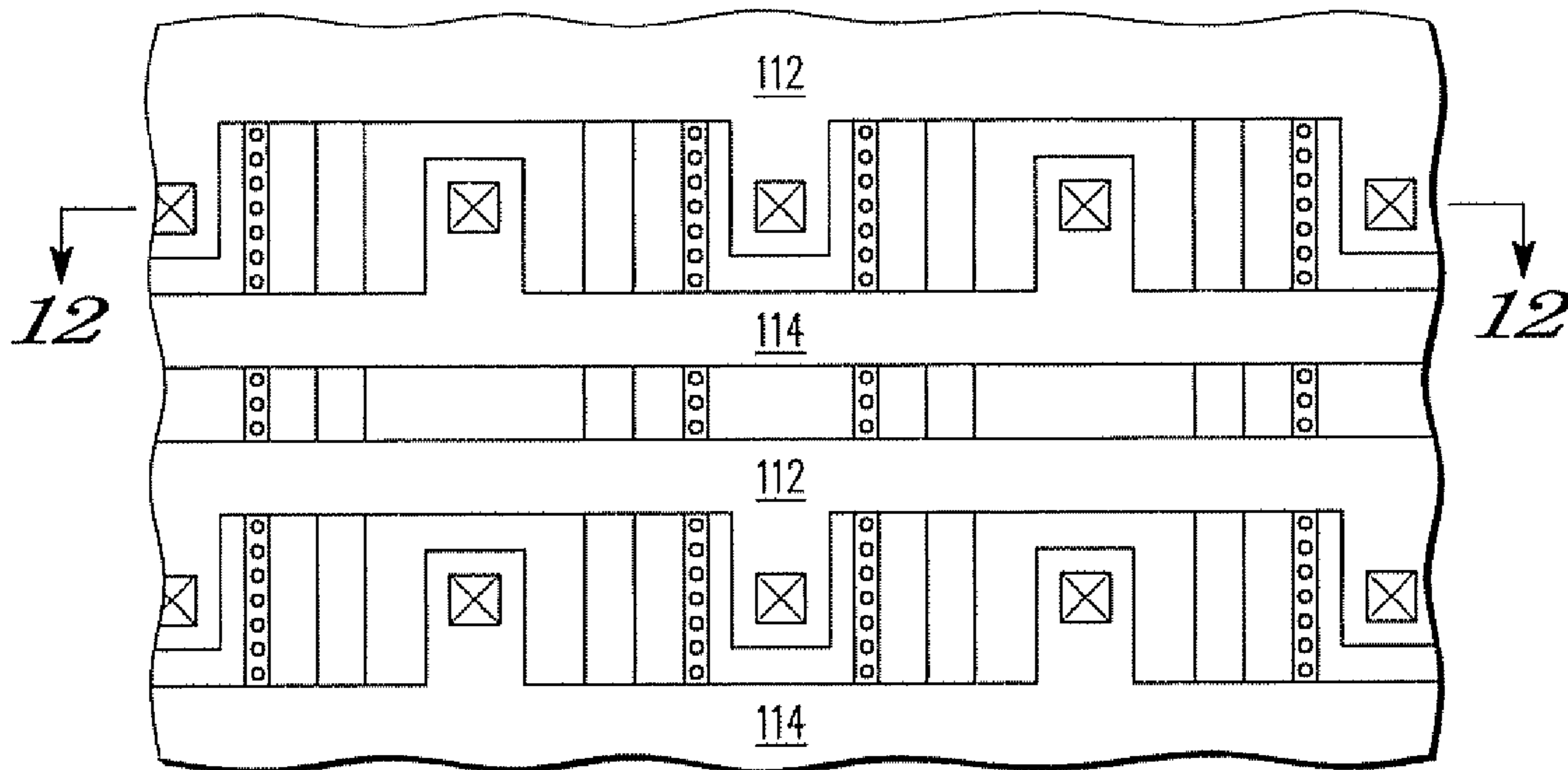


FIG. 11

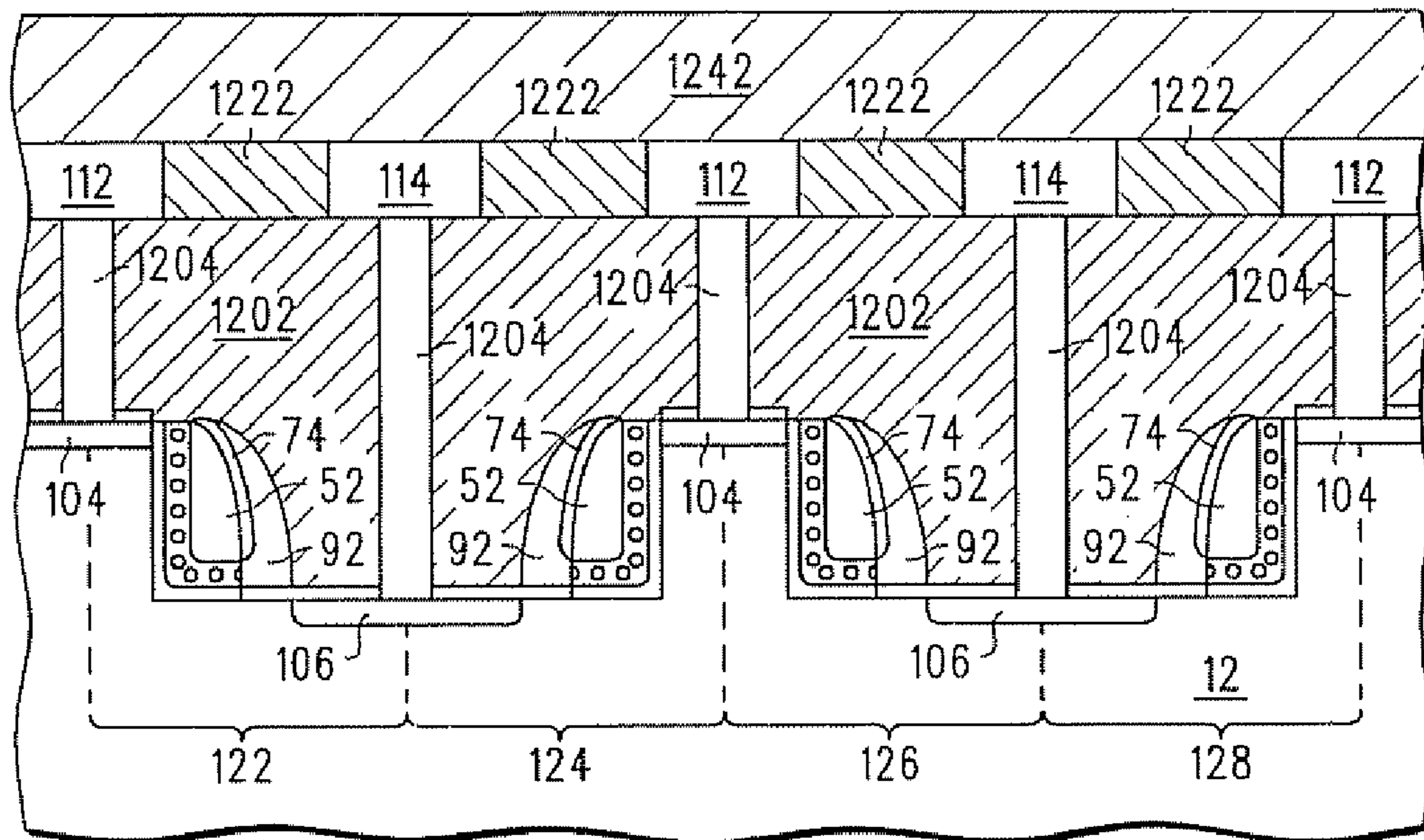


FIG. 12

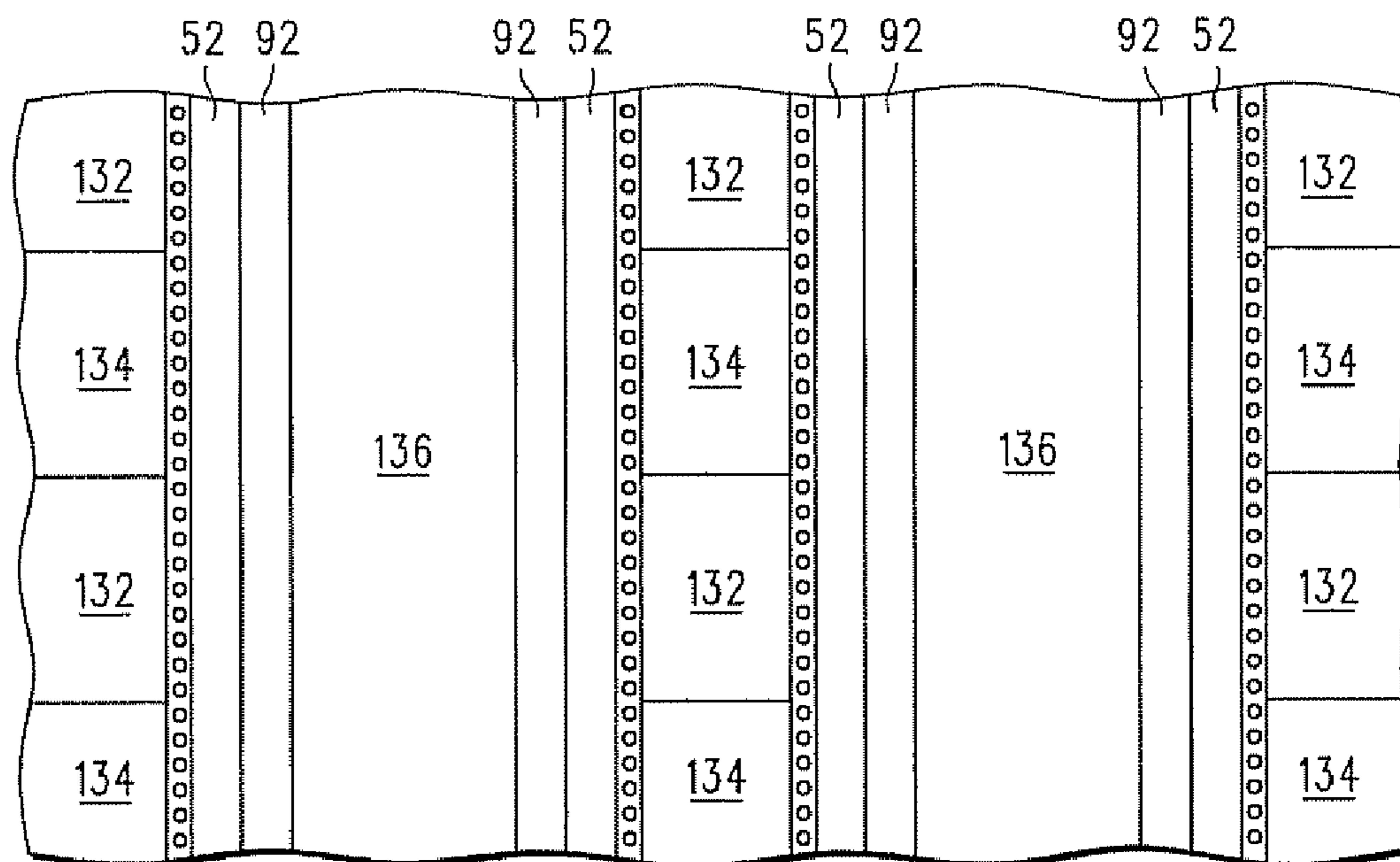


FIG. 13

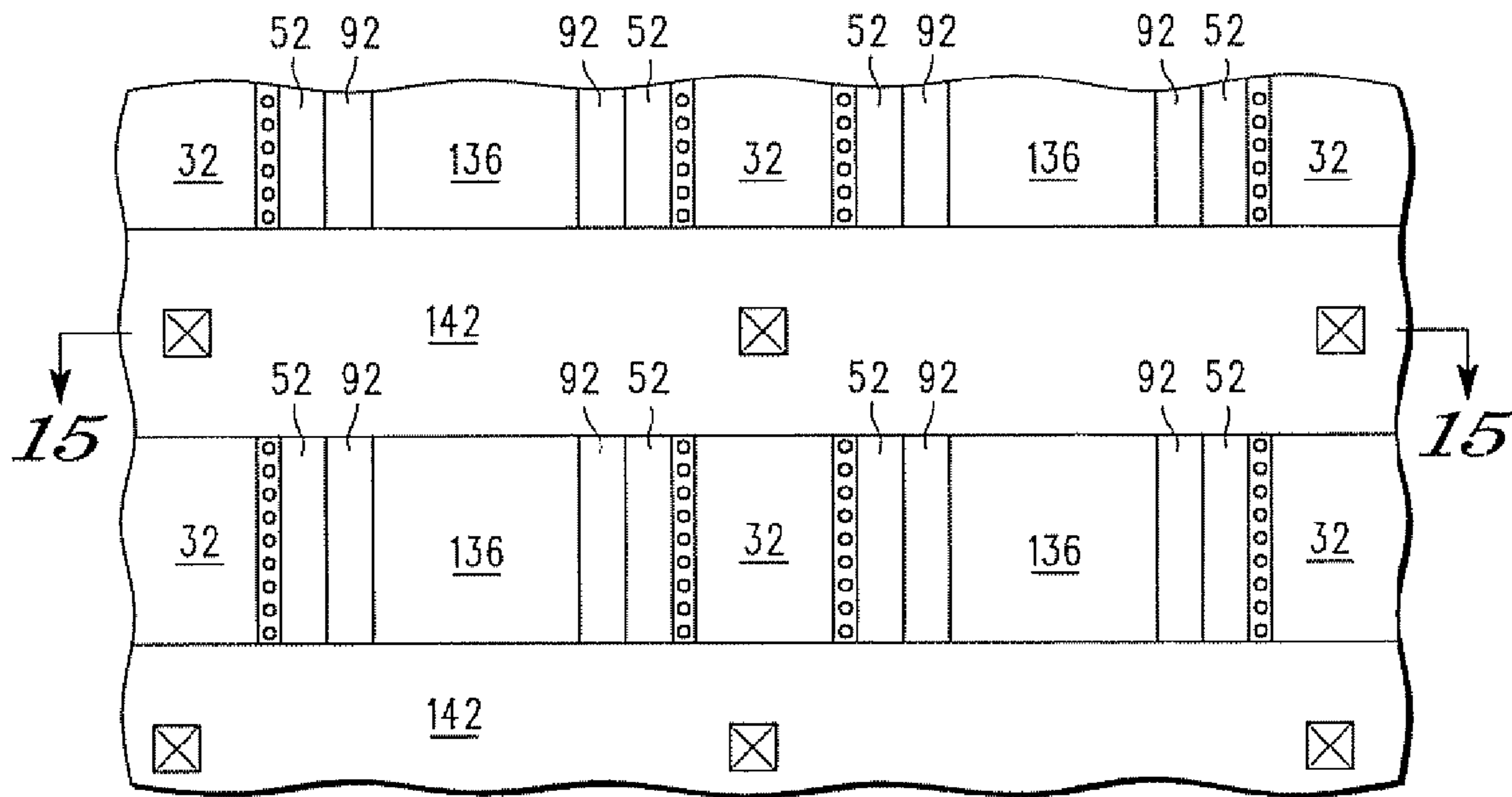


FIG. 14

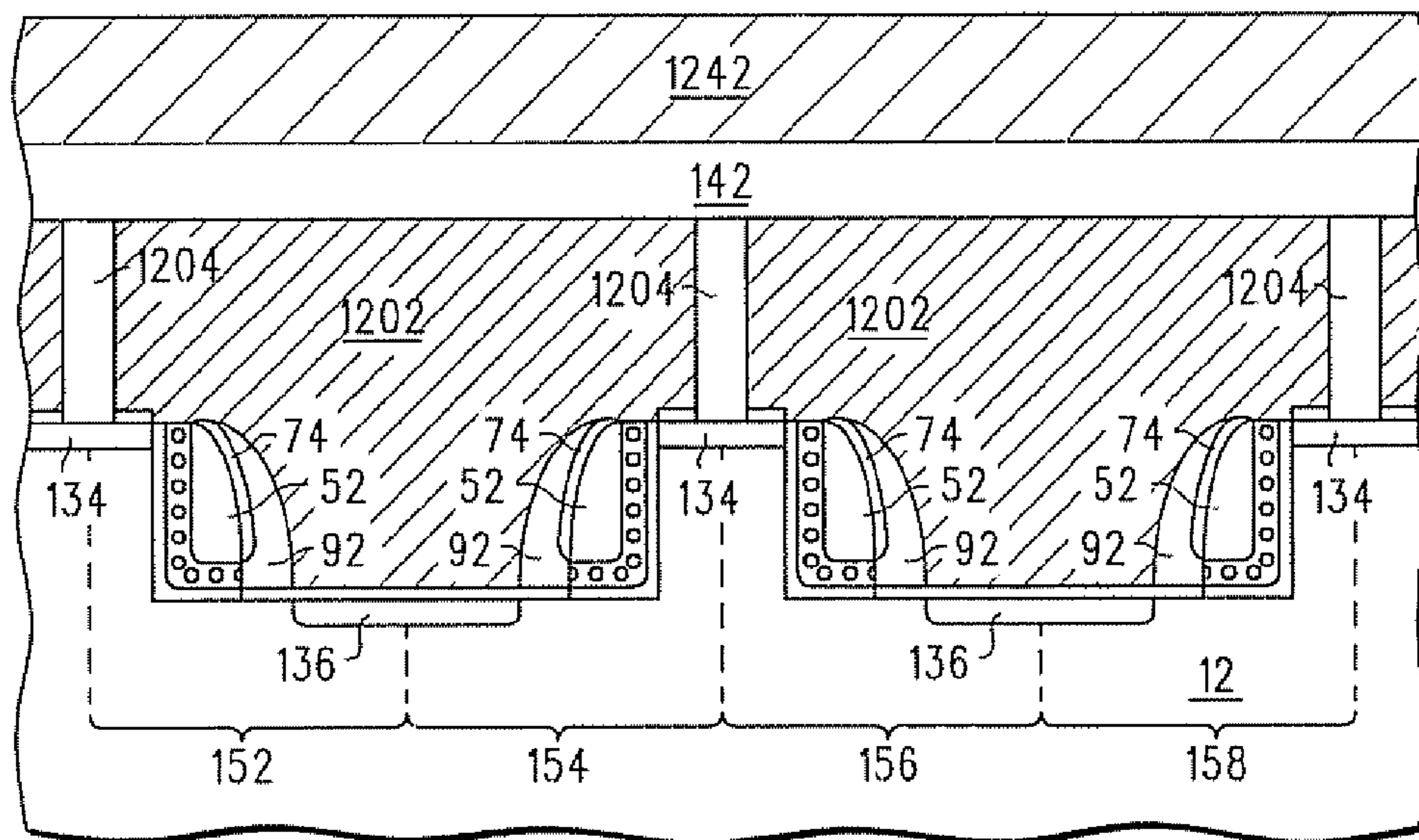


FIG. 15

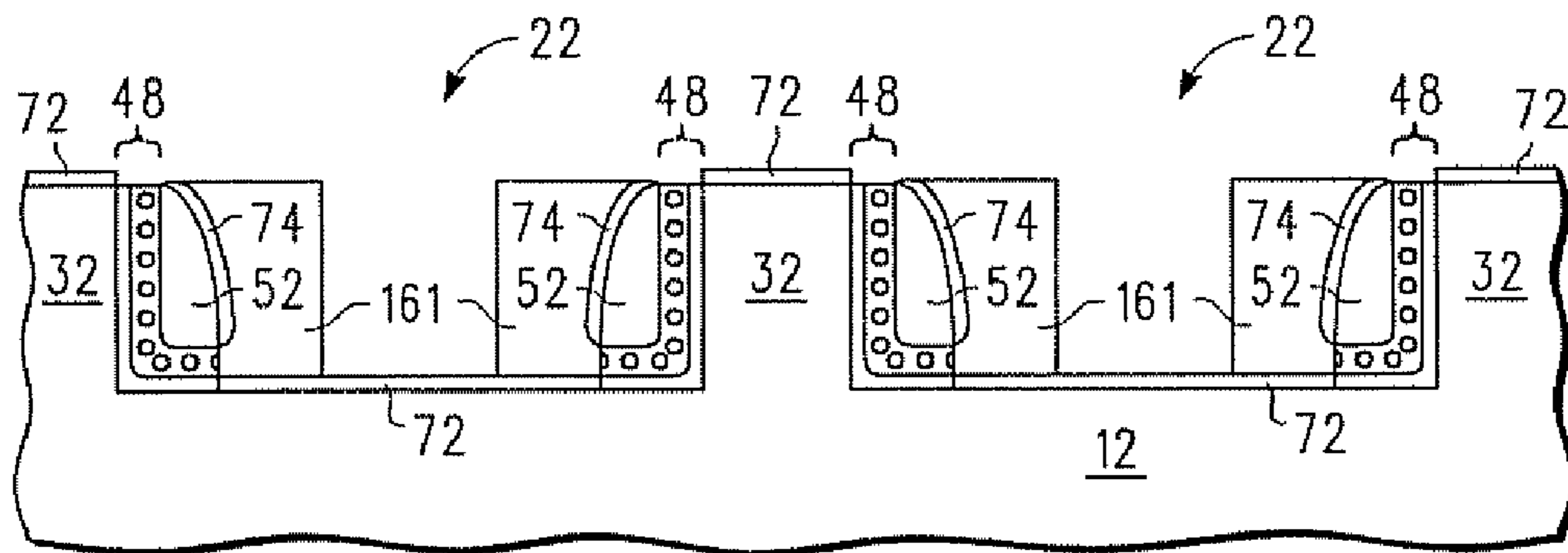


FIG. 16

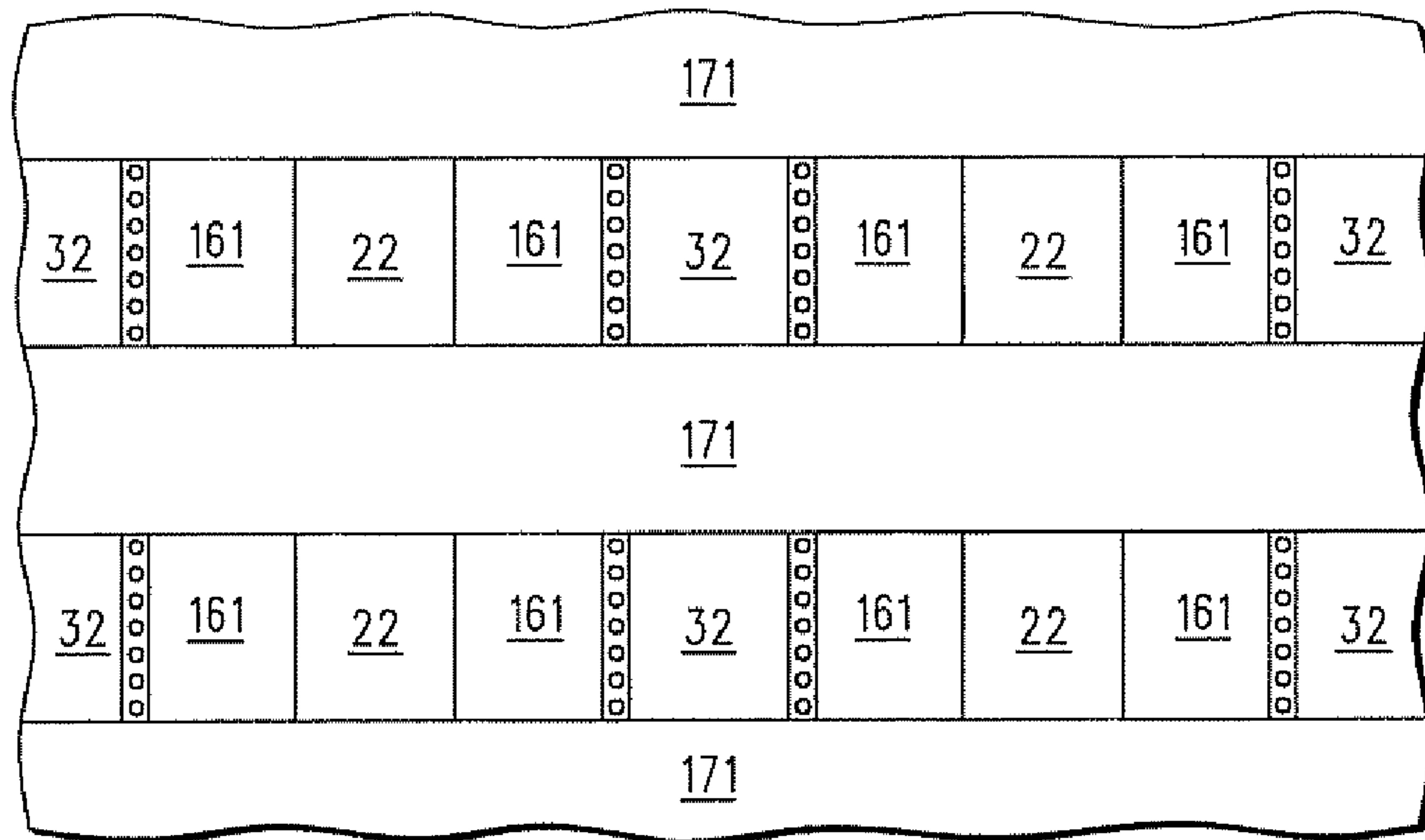


FIG. 17

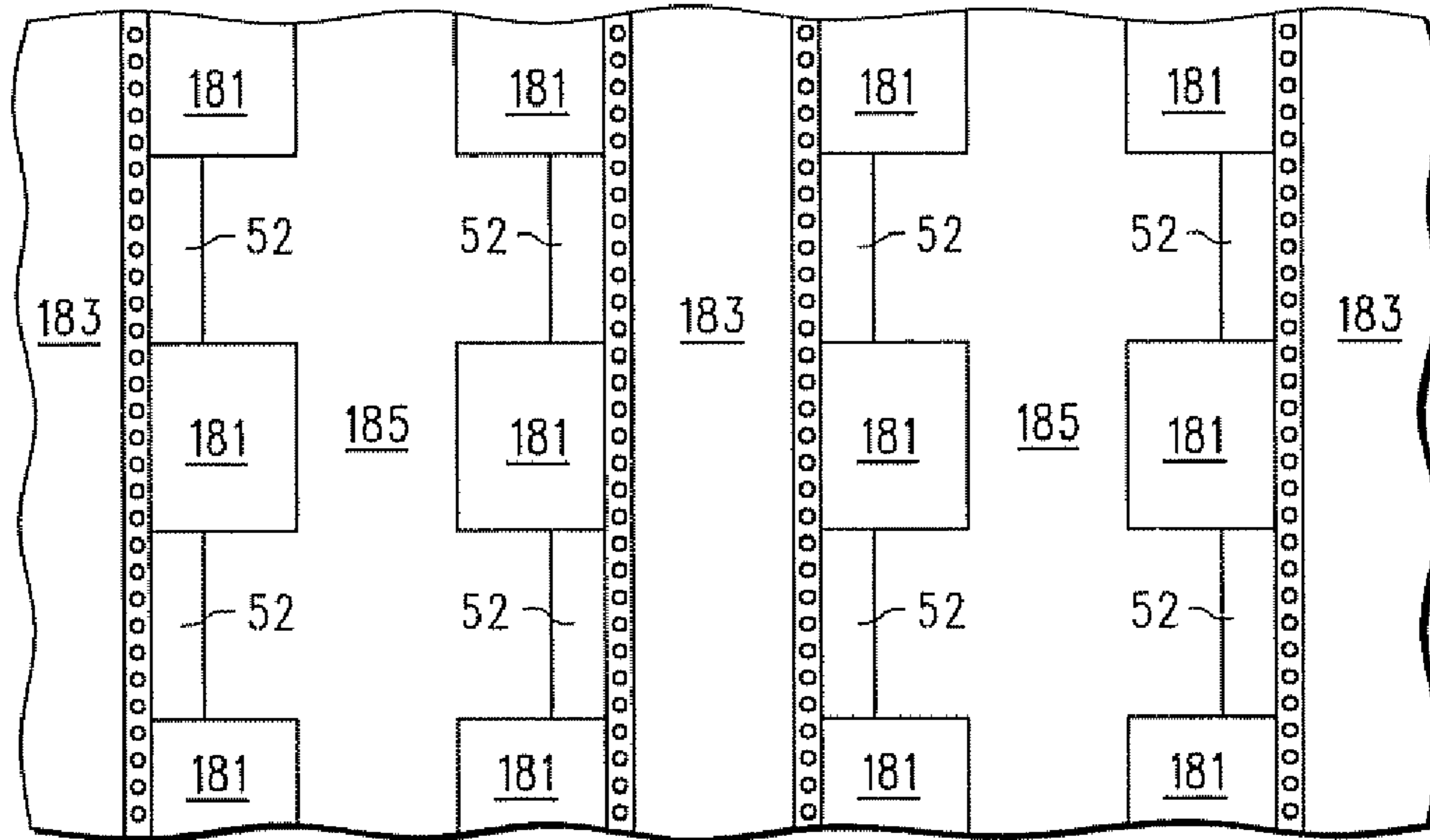


FIG. 18

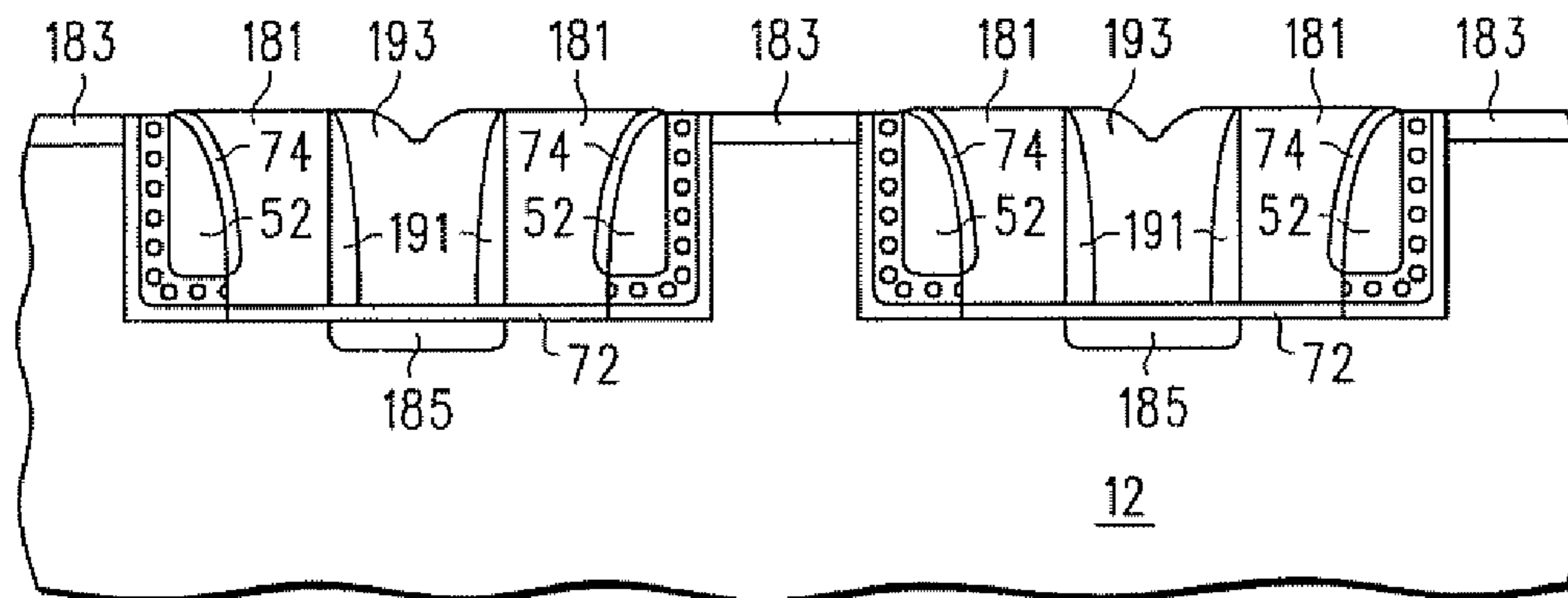


FIG. 19

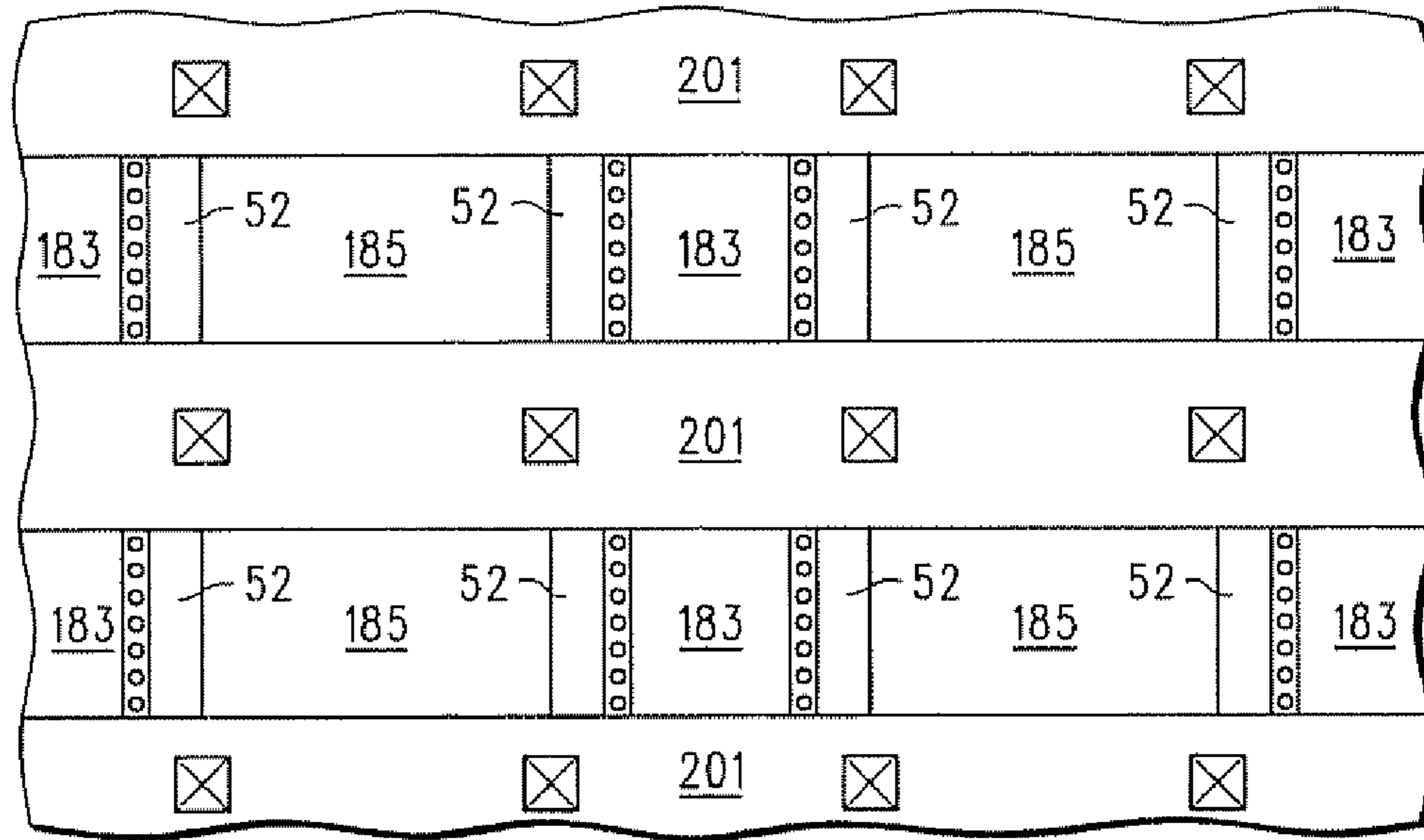


FIG. 20

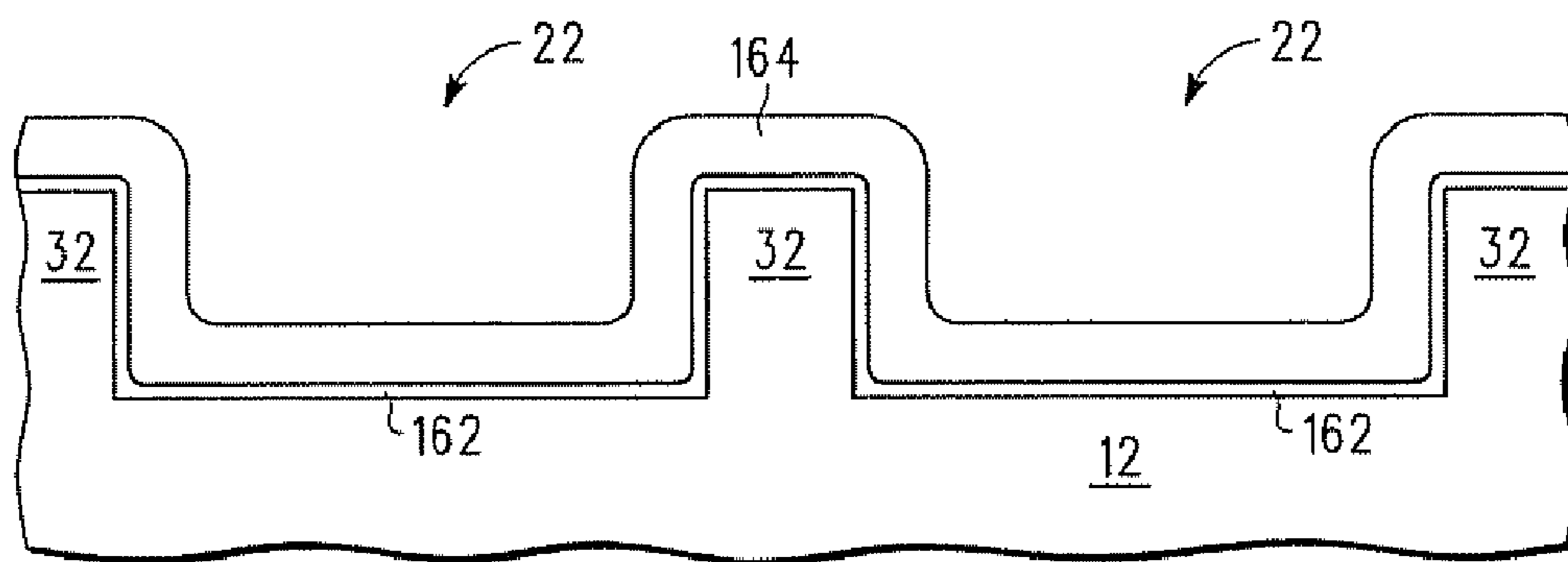


FIG. 21

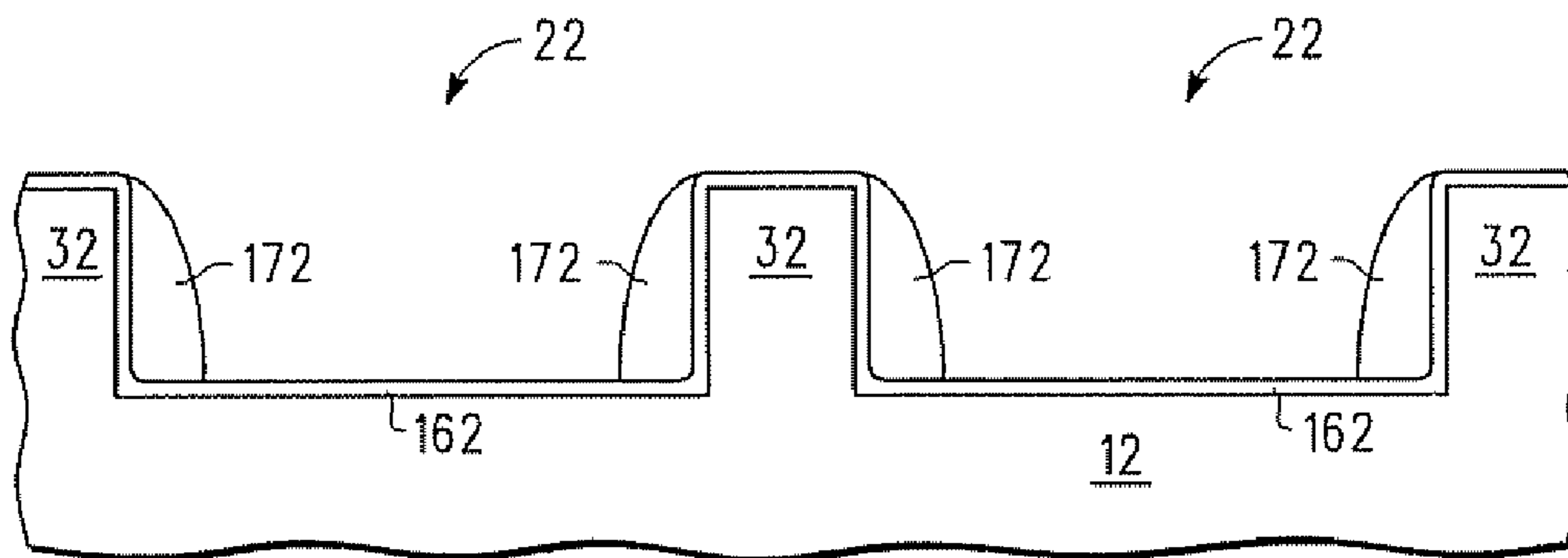


FIG. 22

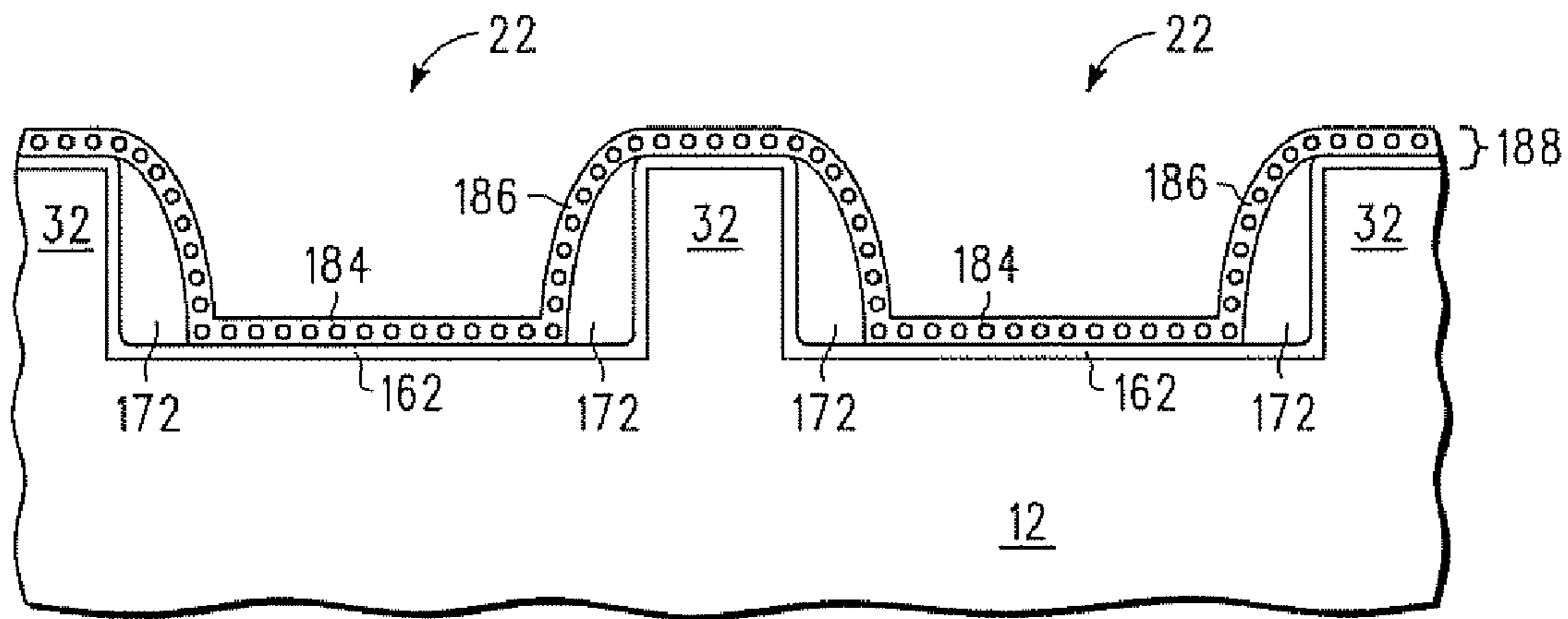


FIG. 23

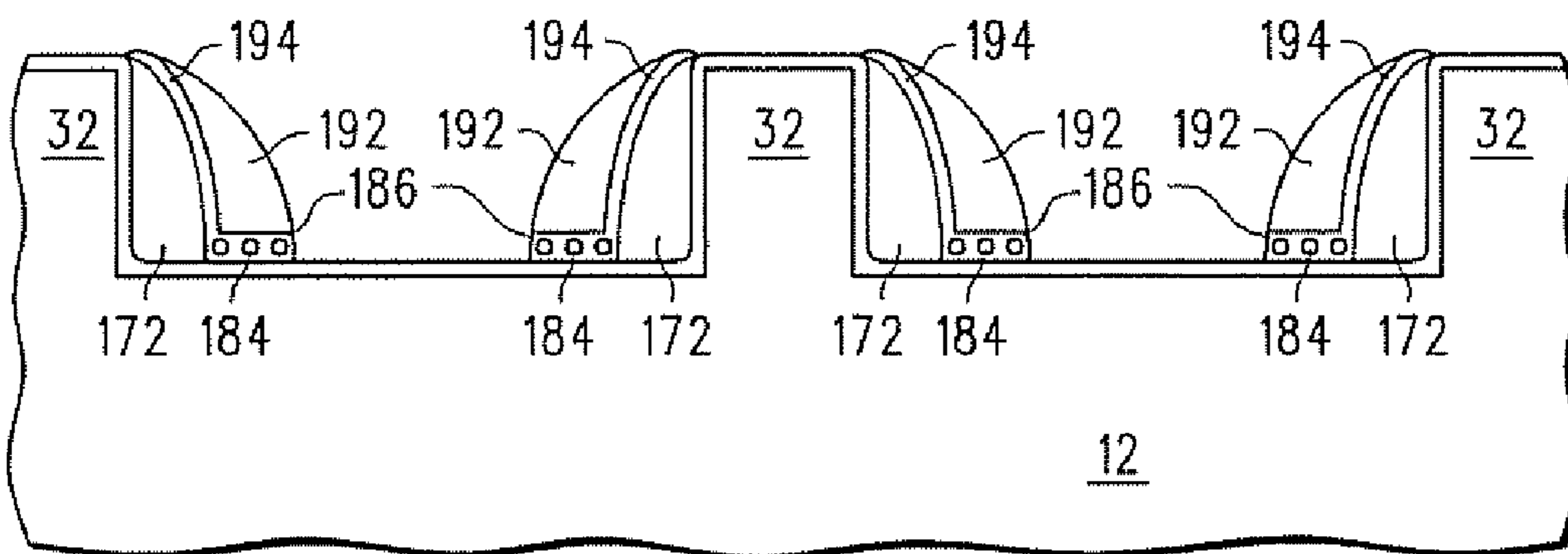


FIG. 24

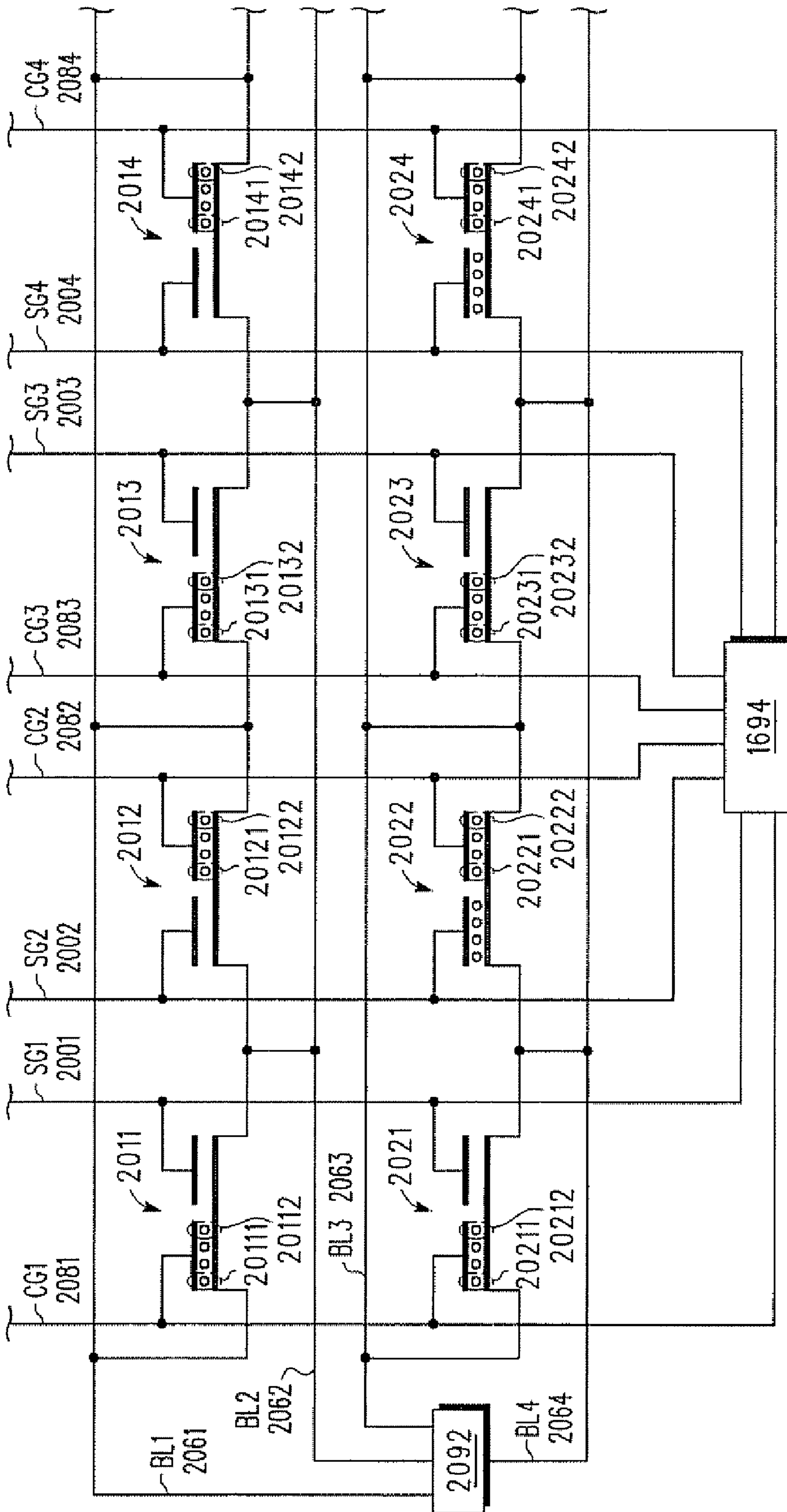


FIG. 25

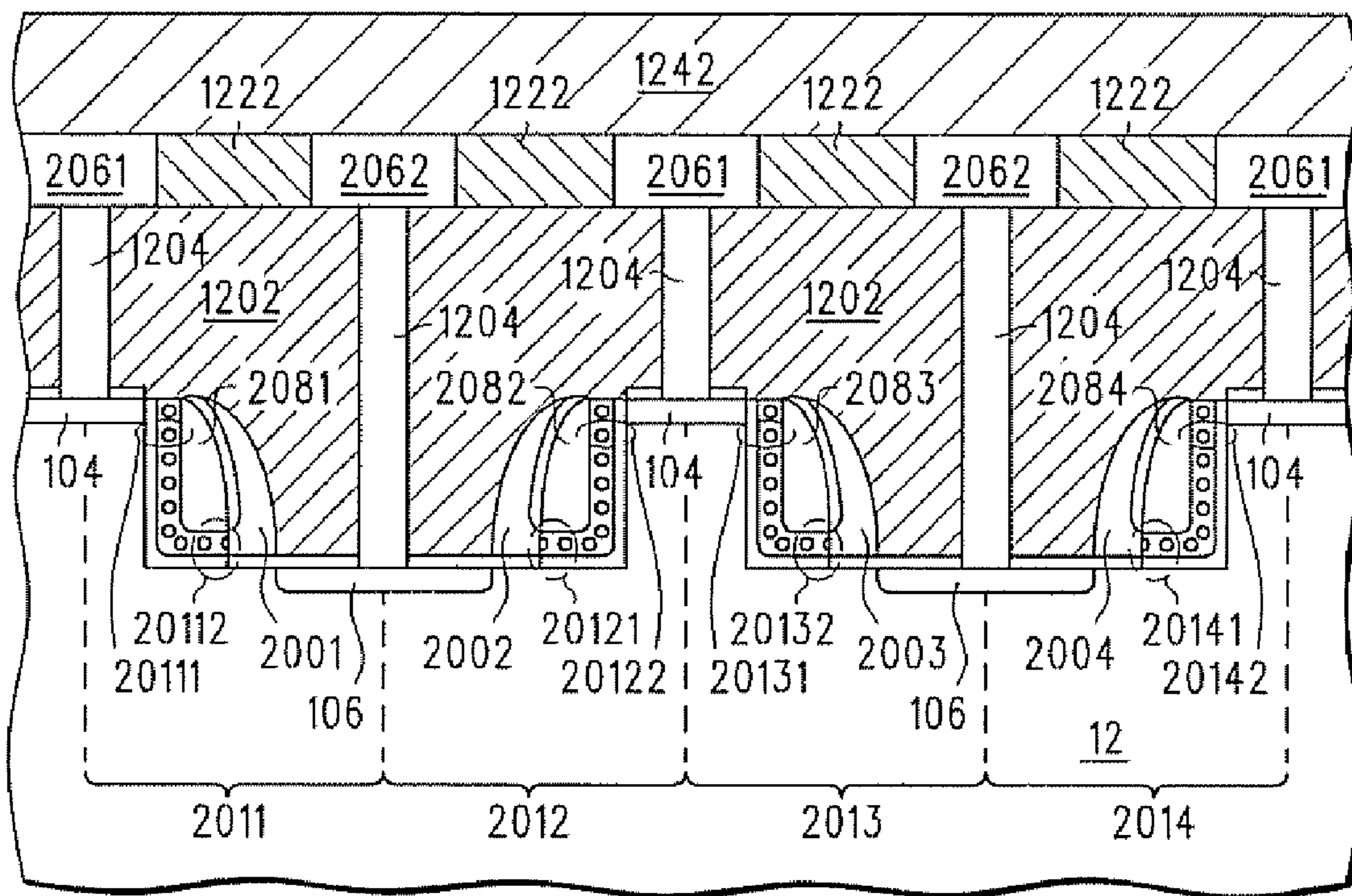


FIG. 26

	CG1 2081	SG1 2001	SG2 2002	CG2 2082	CG3 2083	SG3 2003	SG4 2004	CG4 2084	BL1 2061	BL2 2062	BL3 2063	BL4 2064
PGM 20111	8	6	0	0	0	0	0	0	5	0	FLOAT	FLOAT
READ 20111	3	5	0	0	0	0	0	0	1	0	FLOAT	FLOAT
PGM 20112	8	3	0	0	0	0	0	0	5	0	FLOAT	FLOAT
READ 20112	3	3	0	0	0	0	0	0	2	1	FLOAT	FLOAT
PGM 20121	0	0	6	8	0	0	0	0	5	0	FLOAT	FLOAT
READ 20121	0	0	5	3	0	0	0	0	1	0	FLOAT	FLOAT
PGM 20122	0	0	3	8	0	0	0	0	5	0	FLOAT	FLOAT
READ 20122	0	0	3	3	0	0	0	0	2	1	FLOAT	FLOAT
PGM 20131	0	0	0	0	8	6	0	0	5	0	FLOAT	FLOAT
READ 20131	0	0	0	0	3	5	0	0	1	0	FLOAT	FLOAT
PGM 20132	0	0	0	0	8	3	0	0	5	0	FLOAT	FLOAT
READ 20132	0	0	0	0	3	3	0	0	2	1	FLOAT	FLOAT
PGM 20141	0	0	0	0	0	0	6	8	5	0	FLOAT	FLOAT
READ 20141	0	0	0	0	0	0	5	3	1	0	FLOAT	FLOAT
PGM 20142	0	0	0	0	0	0	3	8	5	0	FLOAT	FLOAT
READ 20142	0	0	0	0	0	0	3	3	2	1	FLOAT	FLOAT
PGM 20211	8	6	0	0	0	0	0	0	FLOAT	FLOAT	5	0
READ 20211	3	5	0	0	0	0	0	0	FLOAT	FLOAT	1	0
PGM 20212	8	3	0	0	0	0	0	0	FLOAT	FLOAT	5	0
READ 20212	3	3	0	0	0	0	0	0	FLOAT	FLOAT	2	1
PGM 20221	0	0	6	8	0	0	0	0	FLOAT	FLOAT	5	0
READ 20221	0	0	5	3	0	0	0	0	FLOAT	FLOAT	1	0
PGM 20222	0	0	3	8	0	0	0	0	FLOAT	FLOAT	5	0
READ 20222	0	0	3	3	0	0	0	0	FLOAT	FLOAT	2	1
PGM 20231	0	0	0	0	8	6	0	0	FLOAT	FLOAT	5	0
READ 20231	0	0	0	0	3	5	0	0	FLOAT	FLOAT	1	0
PGM 20232	0	0	0	0	8	3	0	0	FLOAT	FLOAT	5	0
READ 20232	0	0	0	0	3	3	0	0	FLOAT	FLOAT	2	1
PGM 20201	0	0	0	0	0	0	6	8	FLOAT	FLOAT	5	0
READ 20201	0	0	0	0	0	0	5	3	FLOAT	FLOAT	1	0
PGM 20202	0	0	0	0	0	0	3	8	FLOAT	FLOAT	5	0
READ 20202	0	0	0	0	0	0	3	3	FLOAT	FLOAT	2	1

FIG. 27

ELECTRONIC DEVICE INCLUDING TRENCHES AND DISCONTINUOUS STORAGE ELEMENTS

RELATED APPLICATIONS

This is a divisional application of and claims priority under 35 U.S.C. §120 to U.S. patent application Ser. No. 11/626,768 entitled "Electronic Device Including Trenches and Discontinuous Storage Elements and Processes of Forming and Using the Same" by Li et al., filed Jan. 24, 2007, which is assigned to the current assignee hereof and incorporated herein by reference in its entirety.

This application is related to U.S. patent application Ser. No. 11/626,762 entitled "Electronic Device Including Fins and Discontinuous Storage Elements and Processes of Forming and Using the Same" by Hong et al. filed on Jan. 24, 2007, now U.S. Pat. No. 7,572,699, and Ser. No. 11/626,753 entitled "Electronic Device Including Trenches and Discontinuous Storage Elements and Processes of Forming and Using the Same" by Li et al. filed on Jan. 24, 2007, both of which are assigned to the current assignee hereof.

BACKGROUND

1. Field of the Disclosure

The present invention relates to electronic devices and processes, and more particularly, to electronic devices including trenches and discontinuous storage elements and processes of forming and using the electronic devices.

2. Description of the Related Art

Floating gate non-volatile memories ("FG NVM") are conventional and are commonly used in many applications. The three most common types of programming mechanisms for FG NVM include Fowler-Nordheim tunneling, conventional hot carrier injection, and source-side injection. Fowler-Nordheim tunneling is efficient but is very slow. Efficiency can be measured by dividing the number of carriers that enter a floating gate or one or more other storage elements divided by the number of carriers that enter a memory cell having the floating gate or the other storage element(s). The latter number can be approximated by using the product of the programming current and the programming time.

Hot carrier injection can include conventional hot carrier injection and source-side injection. Both involve the generation of hot carriers, some of which are injected into the floating or the other storage element(s). In conventional hot carrier injection when using a floating gate, an electrical field is generated along a channel region of a memory cell. Within the channel region, the electrical field is the highest near the drain region. The electrical field accelerates carriers flowing within the channel region, such that, within the channel region, the carriers are traveling the fastest near the drain region. A small fraction of carriers collide with silicon or one or more other atoms within the channel region, redirecting the energetic carriers to the floating gate or other charge storage element(s). An electrical field generated by a control gate electrode can help inject some of that small fraction of the hot carriers into the floating gate. Conventional hot carrier injection is inefficient and has high programming current.

Source-side injection is a popular compromise, with respect to efficiency and programming current, between Fowler-Nordheim tunneling and conventional hot carrier injection. With source-side injection, hot carriers are still generated, however, most of the hot carriers are generated within a portion of the channel region that is spaced apart from the drain region. Memory cells designed to be pro-

grammed by source-side injection are not without problems. Typically, the memory cells require one or more additional critical lithographic sequences and result in larger memory cells.

High density floating gate memories are becoming more difficult to fabricate in commercial volumes. As the thickness of the gate dielectric layer decreases, the likelihood of a pinhole or other defect extending through the thickness of the gate dielectric layer increases. Such a defect can cause an electrical short or leakage path between the substrate and the floating gate. The electrical short or leakage path can affect the voltage on the floating gate, and therefore, the memory cell may not be able to retain data. One or more materials may be used for the gate dielectric layer instead of silicon dioxide, however, such material(s) may have other issues, such as material compatibility with other materials used in the memory cell, require new equipment, increase manufacturing costs, etc.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is illustrated by way of example and not limitation in the accompanying figures.

FIG. 1 includes an illustration of a cross-sectional view of a portion of a workpiece after forming a protective layer.

FIGS. 2 and 3 include illustrations of a top view and a cross-sectional view, respectively, of the workpiece of FIG. 1 after forming trenches.

FIG. 4 includes an illustration of a cross-sectional view of a workpiece of FIGS. 2 and 3 after forming a layer of a gate electrode material.

FIG. 5 includes an illustration of a cross-sectional view of a workpiece of FIG. 4 after forming gate electrodes.

FIGS. 6 and 7 include illustrations of a top view and a cross-sectional view, respectively, of the workpiece of FIG. 5 after removing portions of the charge storage stack and forming insulating layers on exposed surfaces of the substrate and gate electrodes.

FIG. 8 includes an illustration of a cross-sectional view of the workpiece of FIGS. 6 and 7 after forming another layer of gate electrode material.

FIG. 9 includes an illustration of a cross-sectional view of the workpiece of FIG. 8 after forming another set of gate electrodes within the trenches.

FIG. 10 includes an illustration of a top view of the workpiece of FIG. 9 after selectively doping portions of the substrate within the mesas and under bottoms of the trenches.

FIGS. 11 and 12 include illustrations of a top view and a cross-sectional view, respectively, of the workpiece of FIG. 10 after forming a substantially completed electronic device.

FIG. 13 includes an illustration of a top view of the workpiece of FIG. 9 after selectively doping portions of the substrate within the mesas and under bottoms of the trenches.

FIGS. 14 and 15 include illustrations of a top view and a cross-sectional view, respectively, of the workpiece of FIG. 13 after forming a substantially completed electronic device.

FIGS. 16 through 20 include illustrations of the workpiece when forming buried bit lines and gate electrodes, wherein the gate electrode are electrically connected to a gate line in accordance with an alternative embodiment.

FIG. 21 includes an illustration of a cross-sectional view of a workpiece of FIGS. 2 and 3 after forming a dielectric layer and a layer of a gate electrode material.

FIG. 22 includes an illustration of a cross-sectional view of a workpiece of FIG. 21 after forming gate electrodes and an insulating layer on exposed surfaces of the substrate and gate electrodes.

FIG. 23 includes an illustration of a cross-sectional view of a workpiece of FIG. 22 after forming a charge storage stack.

FIG. 24 include illustrations of a cross-sectional view of the workpiece of FIG. 23 after forming additional gate electrodes and removing exposed portions of the charge storage stack.

FIGS. 25 through 27 include a circuit schematic diagram, a cross-sectional view of an exemplary physical embodiment of the circuit schematic diagram, and an operating voltage table for memory cells within an NVM array.

Skilled artisans appreciate that elements in the figures are illustrated for simplicity and clarity and have not necessarily been drawn to scale. For example, the dimensions of some of the elements in the figures may be exaggerated relative to other elements to help to improve understanding of embodiments of the invention.

DETAILED DESCRIPTION

An electronic device can include a substrate including a first trench having a first bottom and a first wall. The electrode device can also include a first gate electrode within the first trench and adjacent to the first wall and overlying the first bottom of the first trench, and a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the first bottom of the first trench. The electronic device can further include discontinuous storage elements including a first set of discontinuous storage elements, wherein the first set of the discontinuous storage elements lies between (i) the first gate electrode or the second gate electrode and (ii) the first bottom of the first trench. Processes of forming and using the electronic device are also described.

The processes and structures described allow memory cells or portions thereof to be formed with gate electrodes and doped regions adjacent to the gate electrodes that have dimensions smaller than the resolution limits of lithographic processes. Also, a pair of control gate and select gate electrodes is formed within each trench. Other embodiments described herein allow for an electronic device having a contactless array.

Before addressing details of embodiments described below, some terms are defined or clarified. The term “discontinuous storage elements” is intended to mean spaced-apart objects capable of storing a charge. In one embodiment, substantially all discontinuous storage elements may be initially formed and remain separate from one another. In another embodiment, a substantially continuous layer of material formed an later separated into discontinuous storage elements. In yet another embodiment, substantially all discontinuous storage elements may be initially formed separate from one another, and later during the formation, some but not all of the discontinuous storage elements may coalesce.

The term “oriented” is intended to mean a principal direction in which a feature extends (e.g., from a top view, the longer of two dimensions of the feature, such as the length). As between different features at the same elevation or at different elevations, the features may be oriented substantially parallel, substantially perpendicular, or another angular relationship with respect to each other.

The term “stack” is intended to mean a plurality of layers or a plurality of at least one layer and at least one structure (e.g., nanocrystals), wherein the plurality of layers or plurality of layer(s) and structure(s) provides an electronic function. For example, a nonvolatile memory stack can include layers used to form at least part of a nonvolatile memory cell. A stack may be part of a larger stack. For example, a nonvolatile memory

stack can include a charge storage stack that is used to store charge within a nonvolatile memory cell.

As used herein, the terms “comprises,” “comprising,” “includes,” “including,” “has,” “having” or any other variation thereof, are intended to cover a non-exclusive inclusion. For example, a process, method, article, or apparatus that comprises a list of elements is not necessarily limited to only those elements but may include other elements not expressly listed or inherent to such process, method, article, or apparatus. Further, unless expressly stated to the contrary, “or” refers to an inclusive or and not to an exclusive or. For example, a condition A or B is satisfied by any one of the following: A is true (or present) and B is false (or not present), A is false (or not present) and B is true (or present), and both A and B are true (or present).

Additionally, for clarity purposes and to give a general sense of the scope of the embodiments described herein, the use of the “a” or “an” are employed to describe one or more articles to which “a” or “an” refers. Therefore, the description should be read to include one or at least one whenever “a” or “an” is used, and the singular also includes the plural unless it is clear that the contrary is meant otherwise.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. To the extent not described herein, many details regarding specific materials, processing acts, and circuits are conventional and may be found in textbooks and other sources within the semiconductor and microelectronic arts.

FIG. 1 includes a cross-sectional view of a portion of an electronic device 10, such as an integrated circuit. The integrated circuit can be a standalone memory, a microcontroller, or other integrated circuit that includes a memory. In one embodiment, the electronic device 10 can include a nonvolatile memory (“NVM”) array 18, a portion of which is illustrated in FIG. 1. A substrate 12 can include a monocrystalline semiconductor wafer, a semiconductor-on-insulator wafer, a flat panel display (e.g., a silicon layer over a glass plate), or other substrate conventionally used to form electronic devices. Although not illustrated, shallow trench field isolation may be formed over portions of the substrate 12 in peripheral areas outside of the NVM array 18. The upper most surface of substrate 12 is a primary surface 13. Optionally, the doping concentration of the substrate 12 along the primary surface 13 within the NVM array 18 can be increased using a conventional or proprietary doping operation to potentially reduce leakage current between subsequently-formed gate electrodes that may overlie portions of the primary surface 13. A protective layer 110 can be formed over the primary surface 13 of the substrate 12. The protective layer 110 can include a pad layer 14 and an oxidation-resistant layer 16 over the pad layer 14. The protective layer 110 could have more or fewer layers than are illustrated. The protective layer 110 can remain over the peripheral areas until fabrication of the NVM array 18 is substantially completed. In one embodiment, the pad layer 14 includes oxide, and the oxidation-resistant layer 16 includes nitride.

FIGS. 2 and 3 include illustrations of a top view and a cross-sectional view, respectively, of the memory array after etching trenches 22 to define mesas 32. A patterned resist layer (not illustrated), which includes openings at locations within the NVM array 18 where trenches are to be formed, is formed over the substrate 12 by a conventional or proprietary technique. Exposed portions of the protective layer 110 can then be removed by a conventional or proprietary technique to expose the primary surface 13. In one embodiment, the trenches 22 are formed prior to removal of the patterned resist

layer. The patterned resist layer can then be removed, and the trenches **22** can then be formed by a conventional or proprietary technique. The trenches **22** extend from primary surface **13** and include bottoms **34** and walls **36**. Referring to FIG. **2**, the trenches **22** are oriented substantially parallel to one another. In one embodiment, the depths of trenches **22** are in a range of approximately 50 to approximately 500 nm. In one particular embodiment, the trenches **22** are formed using a timed anisotropic etch to produce the walls **36** that are substantially vertical. In one embodiment, the trenches **22** have substantially uniform depths. The trenches **22** are spaced apart from one another by the mesas **32**, which include remaining portions of the substrate **12** between the trenches **22**. After reading this specification, skilled artisans will appreciate that the trenches **22** can be shallower or deeper in other embodiments. Remaining portions of the protective layer **110** can be removed using a conventional or proprietary technique.

A charge storage stack **48**, including a dielectric layer **42**, discontinuous storage elements **44**, and another dielectric layer **46**, can then be formed, as illustrated in FIG. **4**. The dielectric layer **42** may be thermally grown using an oxidizing or nitridizing ambient, or deposited using a conventional or proprietary chemical vapor deposition technique, physical vapor deposition technique, atomic layer deposition technique, or a combination thereof. The dielectric layer **42** can include one or more films of silicon dioxide, silicon nitride, silicon oxynitride, a high dielectric constant (“high-k”) material (e.g., dielectric constant greater than 8), or any combination thereof. The high-k material can include $\text{Hf}_a\text{O}_b\text{N}_c$, $\text{Hf}_a\text{Si}_b\text{O}_c$, $\text{Hf}_a\text{Si}_b\text{O}_c\text{N}_d$, $\text{Hf}_a\text{Zr}_b\text{O}_c\text{N}_d$, $\text{Hf}_a\text{Zr}_b\text{Si}_c\text{O}_d\text{N}_e$, $\text{Hf}_a\text{Zr}_b\text{O}_c$, $\text{Zr}_a\text{Si}_b\text{O}_c$, $\text{Zr}_a\text{Si}_b\text{O}_c\text{N}_d$, ZrO_2 , other Hf-containing or Zr-containing dielectric material, a doped version of any of the foregoing (lanthanum doped, niobium doped, etc.), or any combination thereof. The dielectric layer **42** has a thickness in a range of approximately 1 to approximately 10 nm. The thickness and material selection of the dielectric layer **42** will substantially determine its electrical properties. In one embodiment the thickness and material are chosen such that the dielectric layer **42** has a silicon dioxide equivalent thickness of less than 10 nm.

The discontinuous storage elements **44** are then formed over NVM array **18**. In one embodiment, discontinuous storage elements **44** overlie the mesas **32** (including the primary surface **13** of the substrate **12**) and lie within trenches **22**. The individual discontinuous storage elements **44** are substantially physically separated from each other. The discontinuous storage elements **44** can include a material capable of storing a charge, such as silicon, a nitride, a metal-containing material, another suitable material capable of storing charge, or any combination thereof. For example, the discontinuous storage elements **44** can include silicon nanocrystals or metal nanoclusters. In one particular embodiment, a substantially continuous layer of amorphous silicon can be formed over exposed surfaces of the substrate **12**. The substantially continuous layer can be exposed to heat or other processing conditions that can cause the layer to “ball up” or otherwise form silicon nanocrystals. The discontinuous storage elements **44** may be undoped, doped during deposition, or doped after deposition. In one embodiment, the discontinuous storage elements **44** can be formed from one or more materials whose properties are not significantly adversely affected during a thermal oxidation process. Such a material can include platinum, palladium, iridium, osmium, ruthenium, rhenium, indium-tin, indium-zinc, aluminum-tin, or any combination thereof. Each of such materials, other than platinum and palladium, may form a conductive metal oxide. In one

embodiment, each of the discontinuous storage elements **44** is no greater than approximately 10 nm in any dimension. In another embodiment, the discontinuous storage elements **44** can be larger, however, the discontinuous storage elements **44** are not formed so large as to form a continuous structure (i.e., all of the discontinuous storage elements **44** are not fused together).

The dielectric layer **46** is then formed over the discontinuous storage elements **44**. The dielectric layer **46** can include one or more dielectric films, any of which may be thermally grown or deposited. The dielectric layer **46** can include any one or more materials or be formed using any of the embodiments as described with respect to the dielectric **42** layer. The dielectric layer **46** can have the same or different composition compared to the dielectric **42** layer and may be formed using the same or different formation technique compared to the dielectric layer **42**.

A gate electrode material **50** is then formed overlying the workpiece and only partly fills remaining portions of the trenches **22**, as illustrated in FIG. **4**. The gate electrode material **50** can include a semiconductor-containing film, a metal-containing film, or any combination thereof. In one embodiment, the gate electrode material **50** includes polysilicon or amorphous silicon. In another embodiment, the gate electrode material **50** may include one or more other materials. In a particular embodiment, the thickness of gate electrode material **50** is not greater than approximately 200 nm, and in another particular embodiment is no greater than 90 nm. In yet another embodiment, the thickness of gate electrode material **50** is at least approximately 20 nm, and in another particular embodiment is at least 50 nm. In a finished device, the gate electrode material **50** can have a dopant concentration of at least $1\text{E}19$ atoms/cm³ when gate electrode material **50** includes polysilicon or amorphous silicon.

The gate electrode material **50** can be deposited by chemical vapor deposition, physical vapor deposition, or a combination thereof. In an embodiment, the gate electrode material **50** can be deposited substantially conformally. In another embodiment, the gate electrode material **50** may not be completely conformal; however, a significant portion of the gate electrode material **50** still forms along the charge storage stack **48** near the walls **36** of the trenches **22**. In one particular embodiment, the gate electrode material **50** is doped when deposited, and in another particular embodiment, is doped after it is deposited.

FIG. **5** includes an illustration of a cross-sectional view after the gate electrode material **50** has been etched to form gate electrodes **52**. In one embodiment, an anisotropic etch is performed to remove portions of gate electrode material **50** overlying the mesas **32** and portions of the bottoms of the trenches **22**. In one embodiment, the gate electrodes **52** are in the form of sidewall spacers and have an arc-shaped outer surface, although other shapes can be used in other embodiments. In one embodiment, the bases of the gate electrodes **52** have widths that are approximately the same as the thickness of the gate electrode material as deposited. In another embodiment, the bases have widths that are at least half of the thickness of the gate electrode material as deposited. In a particular embodiment, each of the bases of the gate electrodes **52** are in a range of approximately 50 to approximately 90 nm wide. The etching chemistry and other etching parameters can use conventional or proprietary etching chemistries and etching parameters used for etching gate electrode materials. Although not illustrated, a mask and etch process sequence can be used to separate the gate electrodes **52** at the ends of the trenches **22**, so that the gate electrodes **52** lying adjacent to opposite sides of the trenches **22** are not electri-

cally shorted to each other. Portions of the charge storage stack **48** overlying the mesas **32** and lying between the gate electrodes **52** within the trenches **22** become exposed.

FIGS. **6** and **7** include illustrations of a top view and a cross-sectional view, respectively, after removing portions of the discontinuous storage elements **44** that are not protected by the gate electrodes **52**. In FIG. **6** and other top views, some dielectric or insulating layers are not illustrated to simplify understanding of positional relationships between features within NVM array **18**. The portions of the discontinuous storage elements **44** can be removed by removing substantially all of the exposed portions of the charge storage stack **48**, removing part of the exposed portions of the charge storage stack **48**, thermally consuming (e.g., oxidizing or nitriding) the portions of the discontinuous storage elements **44**, or any combination thereof. As illustrated in the embodiment of FIG. **6**, the trenches **22**, the mesas **32**, and the gate electrodes **52** are oriented substantially parallel to one another.

In one embodiment, substantially all of the exposed portions of the charge storage stack **48** is removed. In this embodiment, the dielectric layer **46** and the dielectric layer **42** can be etched. In a particular embodiment, the dielectric layer **42** can be removed by a wet etch that undercuts discontinuous storage elements **44**, allowing them to be rinsed away. In another embodiment, exposed portions of dielectric layer **46** are removed, exposing discontinuous storage elements **44**, which can then undergo additional processing to convert them from an electrically conducting material to an electrically insulating material. In one particular embodiment, discontinuous storage elements **44** are silicon nanocrystals that are oxidized to form silicon dioxide. In still another embodiment, the discontinuous storage elements **44** are etched, and the dielectric layer **42** remains. After reading this specification, skilled artisans will appreciate that other processes can be used to selectively remove the discontinuous storage elements **44** that are not protected by the gate electrodes **52**.

As illustrated in the embodiment of FIG. **7**, insulating layers **72** are formed over portions of the substrate **12** within the trenches **22** and over the mesas **32**, and insulating layers **74** are formed along the exposed surfaces of the gate electrodes **52**. The insulating layers **72** and **74** can include an oxide, a nitride, an oxynitride, or any combination thereof. The thickness of the insulating layers **72** acts as an implant screen during a subsequent ion implantation when forming source/drain (“S/D”) regions. The insulating layer **74** helps to protect the gate electrodes **52** during subsequent processing. The insulating layers **72** and **74** can have a thickness in a range of approximately 5 to approximately 50 nm. The insulating layers **72** and **74** can have the same composition or different compositions and the same thickness or different thicknesses.

Many different embodiments can be used in forming the insulating layers **72** and **74**. In one embodiment, exposed portions of the charge storage stack **48** (in FIG. **6**) are removed, and the insulating layers **72** and **74** are formed by thermally oxidizing or nitriding parts of the substrate **12** and the gate electrodes **52**. In another embodiment, the discontinuous storage elements **44** within the exposed portions of the charge storage stack **48** can be thermally oxidized or nitrided while the dielectric layer **42**, and optionally, the dielectric layer **46** are present. While the discontinuous storage elements **44** are being oxidized or nitrided, the insulating layer **74** is formed along the exposed edges of the gate electrodes **52**. In this embodiment, the insulating layer **72** is a composite that includes the dielectric layer **42**, additional insulating material generated from the discontinuous storage elements **44**, and optionally, the dielectric layer **46**, addition

insulating material from the substrate **12** or both the dielectric layer **46** and the additional insulating material. In still another embodiment (not illustrated), an insulating layer may be deposited over the substrate **12** and the gate electrodes **52**, wherein the insulating layer is formed in place of or in conjunction with the insulating layers **72** and **74**. The insulating layer has a composition and thickness as previously described for the insulating layers **72** and **74**. Except as expressly recited herein, each of the insulating layers **72** and **74**, and the deposited insulating layer is formed using a conventional or proprietary technique.

Another layer of gate electrode material **80** is then formed overlying the workpiece and only partly fills remaining portions of the trenches **22**, as illustrated in FIG. **8**. The gate electrode material **80** can include any of the materials, thicknesses, and formation processes as described with respect to the gate electrode material **50**. As compared to the gate electrode material **50**, the gate electrode material **80** may have the same composition or different compositions, the same thickness, or different thicknesses, be formed using by repeating the same process technique or different process techniques, or any combination thereof.

FIG. **9** includes an illustration of a cross-sectional view after the gate electrode material **80** has been etched to form gate electrodes **92**. In one embodiment, an anisotropic etch is performed to remove portions of gate electrode material **80** overlying the mesas **32** and portions of the bottoms of the trenches **22**. In one embodiment, the gate electrodes **92** are in the form of sidewall spacers and have an arc-shaped outer surface, although other shapes can be used in other embodiments. In one embodiment, the bases of the gate electrodes **92** have widths that are approximately the same as the thickness of the gate electrode material as deposited. In another embodiment, the bases have widths that are at least half of the thickness of the gate electrode material as deposited. In a particular embodiment, each of the bases of the gate electrodes **92** are in a range of approximately 50 to approximately 90 nm wide. The etching chemistry and other etching parameters can use conventional or proprietary etching chemistries and etching parameters used for etching gate electrode materials. Although not illustrated, a mask and etch process sequence can be used to separate the gate electrodes **92** at the ends of the trenches **22**, so that the gate electrodes **92** lying adjacent to opposite sides of the trenches **22** are not electrically shorted to each other.

A variety of different layouts for the source/drain (“S/D”) regions, bit lines, and word lines can be used. FIGS. **10** to **12** include a layout in which portions of the substrate **12** adjacent to the gate electrodes **92** and other portions of the substrate **12** adjacent to the gate electrodes **52** are doped, and bit lines are oriented substantially perpendicular to the gate lines. Referring to FIG. **10**, a masking layer is formed over the array and includes masking members **102** and openings between the masking members **102**. The masking members **102** are oriented substantially perpendicular to the gate electrodes **52** and **92**. A dopant is introduced into portions of the substrate between the masking members **102** to form doped regions **104** and **106**. The doped regions **104** include portions of the substrate **12** within the mesas **32**, and the doped regions **106** include portions of the substrate **12** below the bottoms of the trenches **22**. In one embodiment, the doped regions **104** and **106** can act as S/D regions. The dopant may be a p-type dopant (e.g., boron) or an n-type dopant (e.g., phosphorus or arsenic). In one embodiment, the dopant can be introduced using ion implantation. The masking members **102** are then removed by a conventional or proprietary technique. In one embodiment, the implanted dopant is activated by one or

more subsequent thermal cycles, which may or may not serve a different primary purpose such as oxidation, deposition, annealing, drive or activation of a different implant dopant. In one embodiment, each of the doped regions **104** and **106** has a dopant concentration of at least approximately $1E19$ atoms/cm³. The formation of the masking members **102**, their subsequent removal, and doping to form the doped regions **104** and **106** are performed using conventional or proprietary techniques. In one embodiment, the NVM array **18** is now substantially complete other than formation of the electrical connections. Component fabrication within peripheral areas (not illustrated) of the electronic device can be performed using one or more conventional or proprietary techniques.

FIGS. **11** and **12** include illustrations of a top view and a cross-sectional view, respectively, of a substantially completed electronic device. FIG. **11** does not illustrate the insulating layers formed after forming the doped regions **104** and **106** to simplify understanding of the positional relationships between the conductive members (e.g., gate electrodes, doped regions, conductive lines, etc.) of the electronic device. FIG. **11** includes conductive lines **112** and **114** that are oriented substantially perpendicular to the gate electrodes **52** and **92**. In one embodiment, the conductive lines **112** and **114** are bit lines. The conductive lines **112** are electrically connected to the doped regions **104** (within the mesas **32**), and the conductive lines **114** are electrically connected to the doped regions **106** (below the bottoms of the trenches **22**).

FIG. **12** includes a cross-sectional view at sectioning line **12-12** in FIG. **11**. The process is described with respect to FIG. **12**. An interlevel dielectric layer **1202** is formed over the workpiece by a conventional or proprietary technique. The interlevel dielectric layer **1202** is patterned to form contact openings that extend to doped regions **104** and **106** and to other portions of the NVM array **18** that are not illustrated in FIGS. **11** and **12**. The interlevel dielectric layer **1202** can include an insulating material, such as an oxide, a nitride, an oxynitride, or a combination thereof. In a specific embodiment, an anisotropic etch can be used to form contact openings.

Conductive plugs **1204** and the conductive lines **112** and **114** are then formed. The conductive plugs **1204** and the conductive lines **112** and **114** can include the same or different conducting materials. Each of the conductive plugs **1204** and the conductive lines **112** and **114** can include doped silicon, tungsten, titanium, tantalum, titanium nitride, tantalum nitride, aluminum, copper, another suitable conductive material, or any combination thereof. In one particular embodiment, the conductive plugs **1204** include tungsten, and the conductive lines **112** and **114** include copper. An optional barrier layer, adhesion layer, or any combination thereof may be formed before the corresponding conductive layers (e.g., tungsten for the conductive plugs **1204** and copper for the conductive lines **112** and **114**). An optional capping layer (e.g., a metal-containing nitride) may be used to encapsulate copper within the conductive lines **112** and **114**.

In one embodiment, the conductive plugs **1204** are formed before the conductive lines **112** and **114**. In one particular embodiment, a conductive layer (not illustrated) is formed over interlevel dielectric layer **1202** and substantially fills contact openings therein. Portions of the conductive layer that lie outside the contact openings are removed to form the conductive plugs **1204**. In one embodiment, a conventional or proprietary chemical-mechanical polishing operation can be performed, and in another embodiment, a conventional or proprietary etching process can be performed.

Another insulating layer **1222** is then deposited and patterned to form interconnect trenches where the conductive

lines **112** and **114** are formed. Other interconnect trenches can be formed at locations within the NVM array **18**, outside the NVM array **18**, or any combination thereof. In one embodiment, another conductive layer is formed over the interlevel dielectric layer **1202** and substantially fills the interconnect trenches in the insulating layer **1222**. Portions of the conductive layer that lie outside the interconnect trenches within the insulating layer **1222** are removed to form the conductive lines **112** and **114**. In one embodiment, a conventional or proprietary chemical-mechanical polishing operation can be performed, and in another embodiment, a conventional or proprietary etching process can be performed. The insulating layer **1222** lies at substantially the same elevation as and between the conductive lines **112** and **114**. In another embodiment (not illustrated), the conductive plugs **1202** and the conductive lines **112** and **114** are formed concurrently using a conventional or proprietary dual-inlaid process.

In another embodiment (not illustrated), additional insulating and conductive layers can be formed and patterned to form one or more additional levels of interconnects. After the last interconnect level has been formed, an encapsulating layer **1242** is formed over substrate **12**, including the NVM array **18** and peripheral areas. The encapsulating layer **1242** can include one or more insulating Elm, such as an oxide, a nitride, an oxynitride, or a combination thereof. The NVM array **18** includes memory cells **122**, **124**, **126**, and **128**.

FIGS. **13** to **15** illustrate another embodiment having a different layout for the source/drain (“S/D”) regions and bit lines. FIGS. **13** to **15** include a layout in which portions of the substrate **12** adjacent to the gate electrodes **92** and other portions of the substrate **12** adjacent to the gate electrodes **52** are doped, and other bit lines are oriented substantially parallel to the gate electrodes **52** and **92**. In this embodiment, the process through formation of the gate electrodes **92** (FIG. **9**) can be performed using any embodiment as previously described with respect to FIGS. **1** to **9**.

Referring to FIG. **13**, a masking layer is formed over the array and includes masking members **132** and openings between the masking members **132**. As illustrated, the masking members **132** cover portions of the mesas **32**, and in another embodiment, the masking members **132** can cover portions of the gate electrodes **52** and **92** but do not cover portions of the substrate **12** that lie under the trenches **22**. A dopant is introduced into portions of the substrate **12** to form doped regions **134** and **136**. The doped regions **134** include portions of the substrate **12** within the mesas **32**, and the doped regions **136** include portions of the substrate **12** below the bottoms of the trenches **22**. In one embodiment, the doped regions **134** and **136** can act as S/D regions. In the illustrated embodiment, the doped region **136** is oriented substantially parallel to the gate electrodes **52** and **92** and acts as a bit line. The dopant may be a p-type dopant (e.g., boron) or an n-type dopant (e.g., phosphorus or arsenic). In one embodiment, the dopant can be introduced using ion implantation. The masking members **132** are then removed by a conventional or proprietary technique. In one embodiment, the implanted dopant is activated by one or more subsequent thermal cycles, which may or may not serve a different primary purpose such as oxidation, deposition, annealing, drive or activation of a different implant dopant. In one embodiment, each of doped regions **134** and **136** has a dopant concentration of at least approximately $1E19$ atoms/cm³. The formation of the masking members **132**, their subsequent removal, and doping to form the doped regions **134** and **136** are performed using conventional or proprietary techniques. In one embodiment, the NVM array **18** is now substantially complete other than formation of the electrical connections. Component fabrica-

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tion within peripheral areas (not illustrated) of the electronic device can be performed using one or more conventional or proprietary techniques.

FIGS. 14 and 15 include illustrations of a top view and a cross-sectional view, respectively, of a substantially completed electronic device. FIG. 14 does not illustrate the insulating layers after forming the doped regions 134 and 136 to simplify understanding of the positional relationships between the conductive members (e.g., gate electrodes, doped regions, conductive lines, etc) of the electronic device. FIG. 14 includes conductive lines 142 that are oriented substantially perpendicular to the doped regions 136 and the gate electrodes 52 and 92. In one embodiment, the conductive lines 142 are bit lines. The conductive lines 142 are electrically connected to the doped regions 134 (within the mesas 32). Portions of the mesas 32 that were not doped when forming the doped regions 134 are illustrated as mesas 32 in FIG. 14.

FIG. 15 includes a cross-sectional view at sectioning line 15-15 in FIG. 14. The process is described with respect to FIG. 15. The process of forming the interlevel dielectric layer 1202, conductive plugs 1204, and insulating layer 1222 (not illustrated) are formed using any of the embodiments described with respect to FIGS. 11 and 12. The insulating layer 1222 is patterned to form interconnect trenches. Referring to FIG. 14, the remaining portions (not illustrated) of the insulating layer 1222 lie between the conductive lines 142, and the interconnect trenches lie where the conductive lines 142 are to be formed.

The conductive lines 142 are then formed. The conductive lines 142 can include any of the materials as previously described with respect to the conductive plugs 1204 and the conductive lines 112 and 114. More particularly, after the insulating layer 1222 is then deposited and patterned to form interconnect trenches, a conductive layer is formed over the interlevel dielectric layer 1202 and substantially fills the interconnect trenches in the insulating layer 1222. Portions of the conductive layer that lie outside the interconnect trenches within the insulating layer 1222 are removed to form the conductive lines 142. In one embodiment, a conventional or proprietary chemical-mechanical polishing operation can be performed, and in another embodiment, a conventional or proprietary etching process can be performed. The insulating layer 1222 lies at substantially the same elevation as and between the conductive lines 142. In another embodiment (not illustrated), the conductive plugs 1202 and the conductive lines 142 are formed concurrently using a conventional or proprietary dual-inlaid process.

In another embodiment (not illustrated), additional insulating and conductive layers can be formed and patterned to form one or more additional levels of interconnects. After the last interconnect level has been formed, the encapsulating layer 1242 is formed over substrate 12, including the NVM array 18 and peripheral areas. The NVM array 18 includes memory cells 152, 154, 156, and 158.

Another layout can be used in another embodiment (not illustrated). The masking, doping, and bit line orientations described with respect to FIGS. 13 to 15 can be reversed. The doped regions 134 can be continuous along the trenches, and the doped regions 136 can be segmented. The conductive lines 142 would be electrically connected to the doped regions 136, rather than the doped regions 134.

In yet another layout as illustrated in FIGS. 16 to 20, a spacer including a gate electrode material can be segmented into a plurality of gate electrodes to allow word lines, select lines, or other gate lines to be oriented substantially perpendicular to the trenches 22. A workpiece is processed using any

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of the embodiments as described with respect to FIGS. 1 to 8. The gate electrode material 80 (in FIG. 8) is etched to form sidewall spacers 161 as illustrated in FIG. 16. In this embodiment, the sidewall spacers 161 have more of a squared-off shape as compared to the gate electrodes 92 in FIG. 9. The sidewall spacers 161 are formed using a conventional or proprietary processing technique. In a particular embodiment, the sidewall spacers extend along substantially all of the lengths of the trenches 22.

FIG. 17 includes an illustration of a top view after forming a patterned masking layer over the workpiece. A masking layer is deposited and patterned to define the masking members 171. Exposed portions of the sidewall spacers 161 are etched. The sidewall spacer etch is selective to insulating layers. Therefore, the insulating layers 72 protect portions of the substrate 12 within the mesas 32, and the insulating layers 74 protect the gate electrodes 52 when the sidewall spacers 161 are etched. The masking members 171 are then removed. The patterned masking layer formation, sidewall spacer etch, and patterned masking layer removal are performed using convention or proprietary processing operations.

FIG. 18 includes gate electrodes 181, which are remaining portions of the sidewall spacers 161. The gate electrodes 52 are substantially continuous along the walls of the trenches, and portions of the gate electrodes 52 are covered by the gate electrodes 181. Doped regions 183 are formed within the mesas 32, and doped regions 185 are formed along the bottoms of the trenches 22. The doped regions 183 and the doped regions 185 act as source/drain regions and are formed using an embodiment previous described. The trenches 22, the gate electrodes 52, the doped regions 183, and the doped regions 185 are oriented substantially along the same direction.

FIG. 19 includes an illustration of the workpiece after forming insulating spacers 191 and 193. In one embodiment, the insulating spacers 191 and 193 include different material and are formed when forming spacer structures in the logic regions (outside the NVM array 18). The insulating spacers 191 can include an oxide, and the insulating spacers 193 can include a nitride. As illustrated, the two sides of the insulating spacers 193 merge in the middle of the trench 22. If the merge does not occur, a dep-etch-dep process can be formed that preferentially fills in the lowest exposed portions of the trenches, while not forming a significant amount of nitride over the source/drain regions 183, the gate electrodes 181, or any combination thereof. The insulating spacers 191 and 193 are formed using a conventional or proprietary processing sequence.

FIG. 20 includes an illustration of top view of a substantially completed electronic device. Gate lines 201 are formed and are electrically connected to the gate electrodes 181 (not illustrated in FIG. 20) that underlie the gate lines 201. In a particular embodiment, the gate lines 201 act as select gate lines, and the gate electrodes 181 act as select gate electrodes. The gate lines 201 are oriented substantially perpendicular to the trenches 22, the gate electrodes 52, the doped regions 183, the doped regions 185, or any combination thereof. The remaining processing to form the substantially completed electronic device can use any embodiment as described with respect to FIGS. 11 and 12.

Still other layouts can be used but are not illustrated. For example, buried bit lines can be used both within the trenches and outside the trenches. Doped regions within the substrate 12 can extend along the length of the trenches. Spaced-apart field isolation regions can be formed along the bottoms of the trenches 22 before forming the gate electrodes 52 or 92. When forming the doped regions for the S/D regions, as previously described, the spaced-apart field isolation regions help to

form a plurality of spaced-apart doped regions along the bottoms of those trenches that include the spaced-apart field isolation regions. Appropriate bit line contacts can then be made to those spaced-apart doped regions.

In another example (not illustrated), buried bit lines can be formed within the substrate **12**, underlie the trenches **22** and be spaced apart from the bottoms **34** of the trenches **22**. The buried bit lines would be oriented substantially perpendicular to the trenches **22**, similar to the orientation of the conductive lines **142** in FIG. **14**. After forming the buried bit lines, a semiconductor layer can be epitaxial grown over the buried bit lines and have a thickness that is greater than the depth of the trenches. The semiconductor layer can be formed using a conventional or proprietary technique. Trenches are formed using an embodiment previously described. The bottoms **34** of the trenches **22** are spaced apart from the buried bit lines by portions of the semiconductor layer. After forming the trenches **22** and the gate electrodes **62**, a masking layer is formed with masking members within the then be formed within the trenches **22**. The pattern would be similar to the masking layer described with respect to FIG. **13**, except that the masking members would lie within the trenches **22** and would not overlie the mesas **32**. Doping would be performed similar to forming the doped regions **134** and **136** in FIG. **13**. The doped regions **136** extend to the buried bit lines to form an electrical connection. However, the doped regions **134** are spaced apart from the buried bit lines, and therefore, the doped regions **134** are not electrically connected to the buried bit lines below the trenches **22**. In this particular embodiment, a contactless array can be formed. After reading this specification, skilled artisans will appreciate that still other layouts can be used.

FIGS. **21** to **24** illustrate another embodiment in which the location of the discontinuous storage elements is different. In this embodiment, the process through formation of the trenches **22** and removal of the remaining portions of the protective layer **110** can be performed using any embodiment as previously described with respect to FIGS. **1** to **3**. A dielectric layer **162** can be formed along the exposed surface of the substrate **12**, as illustrated in FIG. **21**. The dielectric layer **162** can be formed using any of the materials, thicknesses, and formation techniques as described with respect to the dielectric layer **42**. A gate electrode material **164** is then formed overlying the workpiece and only partly fills remaining portions of the trenches **22**, as illustrated in FIG. **21**. The gate electrode material **164** can be formed using any of the materials, thicknesses, and formation techniques as described with respect to the gate electrode material **50**.

FIG. **22** includes an illustrations of a cross-sectional view after the gate electrode material **164** has been etched to form gate electrodes **172**. The gate electrodes **172** can be formed using any of the previously described embodiments with respect to the gate electrodes **62**. Remaining portions of the protective layer **110** (not illustrated in FIG. **22**) are then removed using a conventional or proprietary technique. A dielectric layer **174** is then formed over portions of the substrate **12** within the trenches **22** and over the mesas **32**, and along the exposed surfaces of the gate electrodes **172**. The dielectric layer **174** can be formed using any of the materials and formation techniques as described with respect to the insulating layer **72** or **74**. The dielectric layer **172** has a thickness in a range of approximately 1 to approximately 9 nm overlying the mesas **32** and portions of the bottoms of the trenches **22**.

FIG. **23** includes an illustration of a cross-sectional view of the workpiece after forming the remainder of the charge storage stack **188**. Discontinuous storage elements **184** are

formed over NVM array **18**. The discontinuous storage elements **184** can be formed using any of the materials, thicknesses, and formation techniques as described with respect to the discontinuous storage elements **44**. A dielectric layer **186** is then formed over the discontinuous storage elements **184**. The dielectric layer **186** can be formed using any of the materials, thicknesses, and formation techniques as described with respect to the dielectric layer **46**. The charge storage stack includes the dielectric layer **174**, the discontinuous storage elements **184**, and the dielectric layer **186**.

In one embodiment, portions of the discontinuous storage elements **184** lying along substantially vertical or more highly sloped surfaces (e.g., along the lower portions of the gate electrodes **172** within the trenches) are removed. In a particular embodiment, a material different from the dielectric layer **174**, the dielectric layer **186**, or both can be formed substantially thicker along substantially horizontal surfaces, as opposed to substantially horizontal surfaces. Different physical vapor or chemical vapor deposition techniques can be used. In a more particular embodiment, the dielectric layers **174** and **186** can include oxide, and a nitride layer (not illustrated) can be deposited using a collimated sputtering technique. An isotropic nitride etchant can remove the nitride layer along the substantially vertical or more highly sloped surfaces, while leaving remaining portions of the nitride layer overlying the substantially horizontal or less highly sloped surfaces. An isotropic oxide etchant can remove exposed portions of the dielectric layer **174** and the dielectric layer **186**, while other portions of the charge storage stack **188** are protected by remaining portions of the nitride layer. After the isotropic oxide etch, the remaining portions of the nitride layer can remain or be removed. In another embodiment (not illustrated), the selective removal process previously described can be omitted, and the charge storage stack **188** can remain along all exposed surfaces.

A gate electrode material is deposited over the workpiece and etched to form gate electrodes **192**, as illustrated in FIG. **24**. The gate electrode material and gate electrodes **192** can be formed using any of the materials, thicknesses, and formation techniques as described with respect to the gate electrode material **50** and the gate electrode **92**. An intergate insulating layer **194** lies between the gate electrodes **172** and **192**. The intergate insulating layer **194** can be formed from portions of the charge storage stack **188**, the gate electrodes **172**, or any combination thereof. Although not illustrated, the process flow can be continued with the formation of doped regions, insulating layers, conductive plugs, conductive lines, and passivation layers using any one or more embodiments as previously described.

The NVM array **18** can include memory cells using any of the layouts as previously described. Circuit schematics and cross references to physical embodiments are described to illustrate better how memory cells within NVM array **18** can be electrically configured and used.

FIG. **25** includes a circuit schematic for an embodiment as described with respect to the embodiment as illustrated in FIG. **26**. Memory cells **2011**, **2012**, **2013**, **2014**, **2021**, **2022**, **2023**, and **2024** are oriented within the NVM array **18**, as illustrated in FIG. **25**.

Referring to FIG. **25**, BL1 **2061** is electrically connected to S/D regions of the memory cells **2011**, **2012**, **2013**, and **2014**, and BL2 **2062** is electrically connected to the other S/D regions of the memory cells **2011**, **2012**, **2013**, and **2014**. BL3 **2063** is electrically connected to S/D regions of the memory cells **2021**, **2022**, **2023**, and **2024**, and BL4 **2064** is electrically connected to the other S/D regions of the memory cells **2021**, **2022**, **2023**, and **2024**.

CG1 2081 is electrically connected to control gate electrodes of the memory cells 2011 and 2021, and SG1 2001 is electrically connected to select gate electrodes of the memory cell 2011 and 2021. CG2 2082 is electrically connected to control gate electrodes of the memory cells 2012 and 2022, and SG2 2002 is electrically connected to select gate electrodes of the memory cell 2012 and 2022. CG3 2083 is electrically connected to control gate electrodes of the memory cells 2013 and 2023, and SG3 2003 is electrically connected to select gate electrodes of the memory cell 2013 and 2023. CG4 2084 is electrically connected to control gate electrodes of the memory cells 2014 and 2024, and SG4 2004 is electrically connected to select gate electrodes of the memory cell 2014 and 2024.

A bit line control module 2092 is coupled to BL1 2061, BL2 2062, and BL3 2063, and BL4 2064. A gate line control module 2094 is coupled to CG1 2081, SG1 2001, SG2 2002, CG2 2082, CG3 2083, SG3 2003, SG4 2004, and CG4 2084. Each of the bit line control module 2092 and the gate line control module 2094 are conventional or proprietary and may include row or column decoders, voltage drivers, other suitable circuits to operate the NVM array 18, or any combination thereof. Each of the bit line control module 2092 and the gate line control module 2094 can include more than one control module. Each of the bit line control module 2092 and the gate line control module 2094 can be biased or electrically float to achieve the proper operation of the NVM array 18.

FIG. 26 illustrates a physical embodiment of a portion of the NVM array 18 corresponding to the row that includes the memory cells 2011, 2012, 2013, and 2014. FIG. 26 is substantially the same as FIG. 12 except that reference numbers as used in the circuit schematics are used in FIG. 26.

Charge storage regions for the memory cells 2011, 2012, 2013, and 2014 are illustrated in FIGS. 25 and 26. The memory cell 2011 includes charge storage regions 20111 and 20112, the memory cell 2012 includes charge storage regions 20121 and 20122, the memory cell 2013 includes charge storage regions 20131 and 20132, and the memory cell 2014 includes charge storage regions 20141 and 20142. The memory cells 2021 to 2024 include similar charge storage regions to the memory cells 2011 to 2014, respectively, but are not illustrated in FIG. 26.

FIG. 27 includes a table that has some of the operating voltages for memory cells along the top row of memory cells, as illustrated in FIG. 25. When programming charge storage region 20111 in accordance with one embodiment, BL1 2061 and BL2 2062 are biased to allow electrons to flow from BL2 2062 to BL1 2061. Each of CG1 2081 and SG1 2001 is biased to allow carriers to flow through the channel region of memory cell 2011. All other gate lines (e.g., CG2 2082, SG2 2002, etc.) are at approximately 0 volts, and BL3 2063 and BL4 2064 are allowed to electrically float. In another embodiment, BL3 2063 and BL4 2064 can be at substantially 0 volts. Referring to FIG. 26, the channel region of the memory cell 2011 allows electrons to flow between BL2 2062 and BL1 2061. The channel region of the memory cell 2011 is adjacent to CG1 2081, SG1 2001, and between the doped regions 104 and 106 that are electrically connected to BL1 2061 and BL2 2062, respectively. More particularly, CG1 2081 and SG2 2001 are biased to allow electrons to flow from BL2 2064 from the doped region 106 to the doped region 104. The electrical field generated in the channel region of the memory cell 2011 near the doped region 104 (via BL1 2061) and CG1 2081 is sufficient to generate hot carriers within the channel region of memory cell 2011 near doped region 104. At least some of the hot carriers are attracted to the discontinuous storage elements at the charge storage region 20111 near the

junction formed near the doped region 94 within the substrate 12. The programming mechanism for programming the charge storage region 20111 is HCI.

The charge storage region 20112 within the memory cell 2011 is not programmed because CG1 2081 and SG1 2001 are at relatively high voltages. Memory cells 2012, 2013, 2014, and 2021 to 2024 are not programmed because the voltages on the other gate lines are at substantially zero volts, and because BL3 2063 and BL4 2064 are electrically float or are at substantially the same voltage so that no current flows between those bit lines.

On a relative basis and when the substrate 12 (or associated well region therein) is biased to zero volts, when programming charge storage region 20111, the voltage differences between CG1 2081 and BL2 2062 and between SG1 2001 and BL2 2062 are in a range of approximately one to two times higher than the voltage difference between BL1 2061 and BL2 2062. In a particular embodiment, the voltage difference between CG1 2081 and BL2 2062 is greater than approximately 1.5 times the voltage difference between BL1 2061 and BL2 2062, and the voltage difference between SG1 2001 and BL2 2062 is no greater than approximately 1.5 times the voltage difference between BL1 2061 and BL2 2062.

Charge storage region 20112 can be programmed using the voltages as listed in FIG. 27. As compared to charge storage region 20111, the voltage on SG1 2002 is reduced. The voltages allow a higher electrical field to be formed in the channel region at a location in the substrate 12 between CG1 2081 and SG1 2001. The relatively low voltage on SG1 2002 allows hot carriers to be more strongly attracted to discontinuous storage elements at charge storage region 20112. The programming mechanism for programming charge storage region 20112 is SSI.

On a relative basis and when the substrate 12 (or associated well region therein) is biased to zero volts, when programming charge storage region 20112, the voltage differences between CG1 2081 and BL2 2062 is in a range of approximately one to two times higher than the voltage difference between BL1 2061 and BL2 2062. CG1 2081 is at a higher potential as compared to SG1 2001. In a particular embodiment, the voltage difference between GL1 2041 and BL2 2062 is no greater than approximately 1.6 times the voltage on BL2 2062, and the voltage difference between SG1 2001 and BL2 2062 is approximately 0.24 to 0.5 times the voltage difference between CG1 2081 and BL2 2062.

Regarding the other charge storage regions and memory cells, charge storage regions, 20122, 20132, and 20362 for memory cells 2012 to 2014 are programmed using SSI. All other charge storage regions within memory cells 2012 to 2014 that have not been described are programmed using HCI. All other charge storage regions for memory cells 2021 to 2024 are similar to memory cells 2011 to 2014, respectively. Each memory cell that includes two gate electrodes can store up to four bits of data, and each memory cell that includes one gate electrode can store up to two bits of data.

In another embodiment, not illustrated, the charge storage region 20111 can be programmed using Fowler-Nordheim tunneling. Programming the charge storage region 20111 can be accomplished by creating a potential difference in a range of about 12 to 16 volts between BL1 2061 and CG1 2081. In one embodiment, erasing can be performed by biasing BL1 2061 to approximately +7 volts, setting the CG1 2081 to approximately -7 volts, and allowing the bit lines to electrically float. Note that the voltages used for BL1 2061 and CG1 2081 do not need to be symmetric with respect to 0 volts. For example, a combination of +5 volts and -9 volts can be used. After reading this specification, skilled artisans will be able to

determine a set of voltages to be used for Fowler-Nordheim tunneling that meets their needs or desires.

Erasing of NVM array **18** can be accomplished by creating a potential difference in a range of about 12 to 16 volts between substrate **12** (or well region therein) and the gate electrodes of the memory cells. In one embodiment, erasing can be performed by biasing substrate **12** (or associated well region therein) to approximately -7 volts, setting the gate lines to approximately $+7$ volts, and allowing the bit lines to electrically float. Note that the voltages used for substrate **12** and the gate lines do not need to be symmetric with respect to 0 volts. For example, a combination of -5 volts and $+9$ volts can be used. After reading this specification, skilled artisans will be able to determine a set of voltages to be used for erasing that meets their needs or desires.

The reading of data within NVM array **18** for memory cells **2011** to **2014** and **2021** to **2024** is given in FIG. **27**. When reading datum at charge storage region **20111** of memory cell **2011**, BL1 **2061** and BL2 **2062** are biased so that electrons flow from BL2 **2062** to BL1 **2061**. SG1 **2001** is biased so that a portion of the channel regions lying adjacent to GL2 **2042** allows carriers to flow. CG1 **2081** is biased to a potential between the programmed and erased threshold voltages. In one particular embodiment, the voltage difference between CG1 **2081** and BL2 **2062** is approximately 0.35 to 0.65 times the voltage difference between SG1 **2001** and BL2 **2062**. A sense amplifier (not illustrated) coupled to the BL1 **2061** or BL2 **2062** will detect a higher level of current when the charge storage region **20111** is not programmed compared to when the charge storage region **20111** is programmed.

As compared to reading datum at charge storage region **20111**, when reading datum at charge storage region **20112**, the voltage on CG1 **2081** is decreased, and the voltages on BL1 **2062** and BL2 **2064** are increased. In a particular embodiment, the voltages on CG1 **2081** and SG1 **2001** are substantially the same, and the voltages on BL1 **2061** and BL2 **2062** are increased by approximately 1 volt. All other voltages can be kept substantially the same, as compared to when reading charge storage region **20111**. In one particular embodiment, the voltage differences between CG1 **2081** and BL2 **2062** and between SG1 **2001** and BL2 **2062** are approximately 1 to 3 times the voltage difference between BL1 **2061** and BL2 **2062**. A sense amplifier (not illustrated) coupled to the BL1 **2061** or BL2 **2062** will detect a higher level of current when the charge storage region **20112** is not programmed compared to when the charge storage region **20112** is programmed. The reading of data at other charge storage regions with memory cells **2012** to **2014**, and **2021** to **2024** can be performed in a similar manner.

Programming, erasing, and reading of memory cells in accordance with the embodiments illustrated in FIGS. **21** to **24** can be performed in a similar manner as, except that the control gate and select gate electrodes are reversed.

The processes and structures described allow memory cells or portions thereof to be formed with gate electrodes and doped regions adjacent to the gate electrodes that have dimensions smaller than the resolution limits of lithographic processes. Also, a pair of control gate and select gate electrodes is formed within each trench. More specifically, the gate electrodes **52** and **92** are in the form of spacers, and the **106** (FIG. **12**) or the doped regions **136** (see FIG. **15**) are adjacent to the gate electrodes **92**. The gate electrodes **52** act as control gate electrodes, and the gate electrodes **92** act as select gate electrodes. The gate electrodes **52** and **92** assist in generating a proper electrical field for SSI or HCI programming. Other embodiments described herein allow for an electronic device having a contactless array.

Many different aspects and embodiments are possible. Some of those aspects and embodiments are described below. After reading this specification, skilled artisans will appreciate that those aspects and embodiments are only illustrative and do not limit the scope of the present invention.

In a first aspect, an electronic device can include a substrate including a first trench having a first bottom and a first wall, a first gate electrode within the first trench and adjacent to the first wall and overlying the first bottom of the first trench, a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the first bottom of the first trench, and discontinuous storage elements including a first set of discontinuous storage elements. The first set of the discontinuous storage elements can lie between (i) the first gate electrode or the second gate electrode and (ii) the first bottom of the first trench.

In one embodiment of the first aspect, the first gate electrode lies between the second gate electrode and the first wall of the first trench. In a particular embodiment, the first set of the discontinuous storage elements also lies between the first gate electrode and the first wall of the first trench. In another particular embodiment, the first set of the discontinuous storage elements also lies between the first gate electrode and the second gate electrode. In still another particular embodiment, the first set of the discontinuous storage elements only lies between the second gate electrode and the bottom of the first trench. In yet another particular embodiment, the electronic device further includes a first source/drain region and a second source/drain region, wherein the substrate has a primary surface, the first source/drain region lies adjacent to the primary surface and the first wall of the first trench, and the second source/drain region lies adjacent to the bottom of the first trench and is spaced apart from the first wall of the first trench. In another embodiment, each of the first gate electrode and the second gate electrode has a shape, which from a cross-sectional view, is a sidewall spacer.

In still another embodiment of the first aspect, the electronic device further includes a third gate electrode and a fourth gate electrode. In this embodiment, the substrate includes a second trench having a second bottom and a second wall, the third gate electrode lies within the second trench and adjacent to the second wall and overlying the second bottom of the second trench, the fourth gate electrode lies within the second trench and adjacent to the third gate electrode and overlying the second bottom of the second trench, and the discontinuous storage elements including a second set of discontinuous storage elements, wherein the second set of the discontinuous storage elements lies between (i) the second bottom of the second trench and (ii) the third gate electrode or the fourth gate electrode.

In a particular embodiment of the first aspect, the electronic device further includes a first source/drain region, a second source/drain region, and a third source/drain region. In this embodiment, the substrate has a primary surface, the first source/drain region lies adjacent to the primary surface, the first wall of the first trench, and the second wall of the second trench, the second source/drain region lies adjacent to the bottom of the first trench and is spaced apart from the first wall of the first trench, and the third source/drain region lies adjacent to the bottom of the second trench and is spaced apart from the second wall of the second trench. In a more particular embodiment, the first gate electrode lies between the first wall of the first trench and the second gate electrode, the first set of the discontinuous storage elements also lies between the first wall of the first trench and the first gate electrode, the third gate electrode lies between the second wall of the second trench and the fourth gate electrode, and the second set of the

discontinuous storage elements also lies between the second wall of the second trench and the third gate electrode.

In a second aspect, a process of forming an electronic device can include forming a first trench within a substrate, wherein the first trench extends from a primary surface of the substrate and has a first wall and a first bottom, forming discontinuous storage elements over the primary surface and within the first trench, forming a first gate electrode within the first trench and adjacent to the first wall and overlying the first bottom of the first trench, forming a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the first bottom of the first trench, and removing a portion of the discontinuous storage elements to form a first set of discontinuous storage elements, wherein the first set of the discontinuous storage elements lies between (i) the first gate electrode or the second gate electrode and (ii) the first bottom of the first trench.

In one embodiment of the second aspect, forming the first gate electrode includes substantially conformally depositing a first gate electrode material over the primary surface of the substrate and within the first trench, and anisotropically etching the gate electrode material to remove a portion of the first gate electrode material from over the primary surface of the substrate to form the first gate electrode. In this embodiment, forming the second gate electrode includes substantially conformally depositing a second gate electrode material over the primary surface of the substrate and the first gate electrode and within the first trench, and anisotropically etching the second gate electrode material to remove a portion of the second gate electrode material from over the primary surface of the substrate to form the second gate electrode.

In another embodiment of the second aspect, forming the discontinuous storage elements is part of forming a charge storage stack, and forming the first gate electrode includes exposing a portion of the charge storage stack. In a particular embodiment, the portion of the discontinuous charge storage elements includes etching the portion of the charge storage stack. In another particular embodiment, removing the portion of the discontinuous charge storage elements includes thermally consuming the portion of the discontinuous charge storage elements.

In still another embodiment of the second aspect, forming the discontinuous storage element is performed after forming the first gate electrode, and removing the portion of the discontinuous charge storage elements is performed after forming the second gate electrode. In a particular embodiment, the process further includes removing another portion of the discontinuous charge storage elements before forming the second gate electrode, wherein the another portion of the discontinuous storage elements overlies the first gate electrode before removing the another portion.

In a third aspect, a process of using an electronic device can include providing a memory cell. The memory cell can include a substrate having a primary surface and including a first trench having a first bottom and a first wall, a first gate electrode within the first trench and adjacent to the first wall and overlying the first bottom of the first trench, and a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the first bottom of the first trench. The memory cell can also include discontinuous storage elements including a first set of discontinuous storage elements, wherein the first set of the discontinuous storage elements can lie between the first gate electrode and the first bottom of the first trench, and can lie between the first gate electrode and the first wall. The memory cell can also include a first source/drain region lying adjacent to the primary surface and the first wall of the first trench and coupled to a first

bit line, and a second source/drain region lying adjacent to the bottom of the first trench and is spaced apart from the first wall of the first trench and coupled to a second bit line. The process can also include programming a first bit of the memory cell including biasing the first bit line and the second bit line at a first voltage difference, biasing the second gate electrode, such that a second voltage difference between the second gate electrode and the first bit line is no greater than approximately half of the first voltage difference, and biasing the first gate electrode, such that a third voltage difference between the first gate electrode and the first bit line is in a range of approximately 0.5 to approximately 1.5 times the first voltage difference.

In one embodiment of the third aspect, the process further includes programming a second bit of the memory cell including biasing the first bit line and the second bit line at a fourth voltage difference, biasing the first gate electrode, such that a fifth voltage difference between the first gate electrode and the second bit line is in a range of approximately 0.5 to approximately 1.5 times the first voltage difference, and biasing the second gate electrode, such that a sixth voltage difference between the second gate electrode and the second bit line is in a range of approximately 0.5 to approximately 1.5 times the first voltage difference.

In another embodiment of the third aspect, the process further includes erasing the memory cell including biasing the substrate and the first gate electrode at a fourth voltage difference, such that the fourth voltage difference has an opposite polarity compared to first voltage difference, and the fourth voltage difference has a magnitude that is at least approximately 4 times a magnitude of the first voltage difference, and electrically floating the first bit line and the second bit line.

Note that not all of the activities described above in the general description or the examples are required, that a portion of a specific activity may not be required, and that one or more further activities may be performed in addition to those described. Still further, the order in which activities are listed are not necessarily the order in which they are performed. After reading this specification, skilled artisans will be capable of determining what activities can be used for their specific needs or desires.

Any one or more benefits, one or more other advantages, one or more solutions to one or more problems, or any combination thereof have been described above with regard to one or more specific embodiments. However, the benefit(s), advantage(s), solution(s) to problem(s), or any element(s) that may cause any benefit, advantage, or solution to occur or become more pronounced is not to be construed as a critical, required, or essential feature or element of any or all the claims.

The above-disclosed subject matter is to be considered illustrative, and not restrictive, and the appended claims are intended to cover all such modifications, enhancements, and other embodiments that fall within the scope of the present invention. Thus, to the maximum extent allowed by law, the scope of the present invention is to be determined by the broadest permissible interpretation of the following claims and their equivalents, and shall not be restricted or limited by the foregoing detailed description.

What is claimed is:

1. An electronic device comprising:

a substrate including a portion that defines a first trench having a first bottom, a first wall, and a second wall opposite the first wall;

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- a first gate electrode within the first trench and adjacent to the first wall and overlying the first bottom of the first trench;
- a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the first bottom of the first trench, wherein the first gate electrode lies between the first wall and the second gate electrode;
- a first set of discontinuous storage elements, wherein the first set of discontinuous storage elements lies between (i) the first gate electrode or the second gate electrode and (ii) the first bottom of the first trench;
- a third gate electrode within the first trench and adjacent to the second wall and overlying the first bottom of the first trench;
- a fourth gate electrode within the first trench and adjacent to the third gate electrode and overlying the first bottom of the first trench, wherein the third gate electrode being between the second wall and the fourth gate electrode;
- a second set of discontinuous storage elements, wherein the second set of discontinuous storage elements lies between (i) the third gate electrode or the fourth gate electrode and (ii) the first bottom of the first trench; and wherein a first memory cell comprises the first gate electrode, the second gate electrode, and the first set of discontinuous storage elements; a second memory cell comprises the third gate electrode, the fourth gate electrode, and the second set of discontinuous storage element; and the second gate electrode being between the first gate electrode and the fourth gate electrode.
2. The electronic device of claim 1, wherein the second gate electrode is conformal to the first gate electrode.
3. The electronic device of claim 2, wherein:
the first gate electrode is a select gate electrode;
the second gate electrode is a control gate electrode; and
the first set of the discontinuous storage elements only lies between the second gate electrode and the bottom of the first trench, and substantially no discontinuous storage elements lie between the second gate and the first wall.
4. The electronic device of claim 2, further comprising a first source/drain region and a second source/drain region, wherein:
the substrate has a primary surface;
the first source/drain region lies within the substrate and adjacent to the primary surface and the first wall of the first trench; and
the second source/drain region lies within the substrate and adjacent to the bottom of the first trench and is spaced apart from the first wall of the first trench.
5. The electronic device of claim 1, wherein within the first memory cell, substantially all of the first and second gate electrodes lie within the first trench.
6. The electronic device of claim 1, wherein each of the first gate electrode and the second gate electrode has a shape, which from a cross-sectional view, is a sidewall spacer.
7. The electronic device of claim 1, further comprising a fifth gate electrode, a sixth gate electrode, and a third set of discontinuous storage elements, wherein: the substrate including another portion that defines a second trench having a second bottom and a second wall; the fifth gate electrode lies within the second trench and adjacent to the second wall and overlying the second bottom of the second trench; the sixth gate electrode lies within the second trench and adjacent to the fifth gate electrode and overlying the second bottom of the second trench; and the third set of the discontinuous storage elements lies between (i) the second bottom of the second trench and (ii) the fifth gate electrode or the sixth gate electrode.

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8. The electronic device of claim 7, further comprising a first source/drain region, a second source/drain region, and a third source/drain region, wherein:
the substrate has a primary surface;
the first source/drain region lies within the substrate and adjacent to the primary surface, the first wall of the first trench, and the second wall of the second trench;
the second source/drain region lies within the substrate and adjacent to the bottom of the first trench and is spaced apart from the first wall of the first trench; and
the third source/drain region lies adjacent to the bottom of the second trench and is spaced apart from the second wall of the second trench.
9. An electronic device comprising: a substrate including a portion that defines a first trench having a bottom, a first wall, and a second wall opposite the first wall; a first gate electrode within the first trench and adjacent to the first wall and overlying the bottom of the first trench; a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the bottom of the first trench, wherein the first gate electrode lies between the first wall and the second gate electrode; and a first set of discontinuous storage elements, wherein the set of discontinuous storage elements lies between the first gate electrode and the bottom of the first trench; a third gate electrode within the first trench and adjacent to the second wall and overlying the bottom of the first trench; a fourth gate electrode within the first trench and adjacent to the third gate electrode and overlying the bottom of the first trench, wherein the third gate electrode being between the second wall and the fourth gate electrode; a second set of discontinuous storage elements, wherein the second set of discontinuous storage elements lies between (i) the third gate electrode or the fourth gate electrode and (ii) the first bottom of the first trench; and wherein a first memory cell comprises the first gate electrode, the second gate electrode, and the first set of discontinuous storage elements; a second memory cell comprises the third gate electrode, the fourth gate electrode, and the second set of discontinuous storage element; and the second gate electrode being between the first gate electrode and the fourth gate electrode.
10. The electronic device of claim 9, wherein substantially no discontinuous storage element lies between a bottom surface of the second gate electrode and the bottom of the first trench.
11. The electronic device of claim 9, wherein:
within the first memory cell, substantially all of the first and second gate electrodes lie within the first trench;
the substrate includes other portions that define other trenches and other sets of discontinuous storage elements lying within the other trenches; and
substantially all of the discontinuous storage elements lie within the first and other trenches.
12. An electronic device comprising: a substrate including a portion that defines a first trench having a bottom and a first wall and a second wall opposite the first wall; a first gate electrode within the first trench and adjacent to the first wall and overlying the bottom of the first trench; a second gate electrode within the first trench and adjacent to the first gate electrode and overlying the bottom of the first trench; wherein the first gate electrode lies between the first wall and the second gate electrode; and a first set of discontinuous storage elements, wherein the set of discontinuous storage elements lies between the second gate electrode and the bottom of the first trench; a third gate electrode within the first trench and adjacent to the second wall and overlying the bottom of the first trench; a fourth gate electrode within the first trench and adjacent to the third gate electrode and overlying the bottom

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of the first trench, wherein the third gate electrode being between the second wall and the fourth gate electrode; a second set of discontinuous storage elements, wherein the second set of discontinuous storage elements lies between (i) the third gate electrode or the fourth gate electrode and (ii) the first bottom of the first trench; and wherein a memory cell comprises the first gate electrode, the second gate electrode, and the set of discontinuous storage elements, a second memory cell comprises the third gate electrode, the fourth gate electrode, and the second set of discontinuous storage element; and the second gate electrode being between the first gate electrode and the fourth gate electrode.

13. The electronic device of claim 12, wherein:
 the first gate electrode is a select gate electrode;
 the second gate electrode is a control gate electrode; and
 the first set of discontinuous storage elements is spaced apart from the wall of the first trench.

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14. The electronic device of claim 13, wherein within the device, substantially all of the first, second, third, and fourth gate electrodes lie within the first trench.

15. The electronic device of claim 14, wherein substantially no discontinuous storage element lies between the first gate electrode and the bottom of the first trench.

16. The electronic device of claim 12, wherein substantially no discontinuous storage element lies between the first gate electrode and the bottom of the first trench.

17. The electronic device of claim 12, wherein:
 the substrate includes other portions that define other trenches;

other sets of discontinuous storage elements lie within the other trenches; and

substantially all of the discontinuous storage elements of a memory array that includes the first and second memory cells lie within the first and other trenches.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

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Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Claims:

In Column 22, Line 34, please change "first bottom" to --bottom--.

Signed and Sealed this
Fourth Day of June, 2013



Teresa Stanek Rea
Acting Director of the United States Patent and Trademark Office